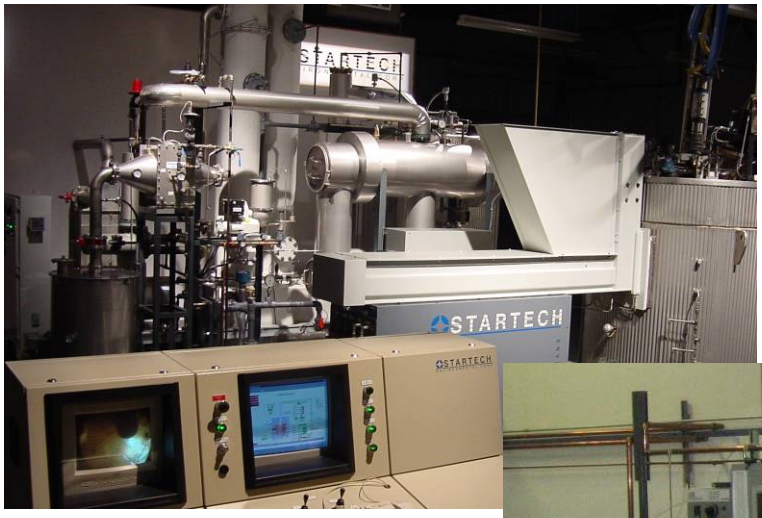
STARTECH ENVIRONMENTAL CORP.

U.S. Department of Energy
Energy Efficiency and Renewable Energy

# Startech Hydrogen Production
# Final Technical Report
# November 2007




**Prepared for:**

Department of Energy
Golden Field Office
1617 Cole Boulevard
Golden, Colorado 80401-3393
Award No: DE-FC36-04GO14233

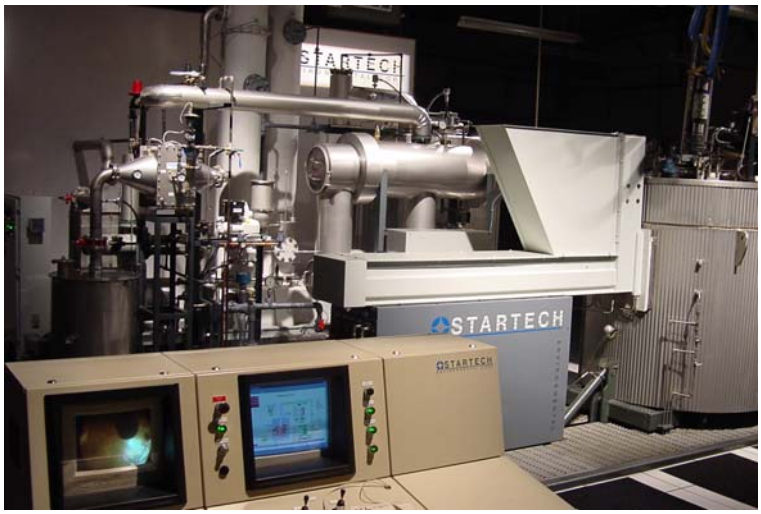
The Final Technical Report submitted is a composite of Phase 1 and Phase 2 technical reports. Both reports are included in this document in their entirety.

STARTECH
ENVIRONMENTAL CORP.

U.S. Department of Energy
Energy Efficiency and Renewable Energy

# Startech Hydrogen Production

# Phase 1 Technical Report




January 2006

**Prepared for:**

Department of Energy
Golden Field Office
1617 Cole Boulevard
Golden, Colorado 80401-3393
Award No: DE-FC36-04GO14233

# Table of Contents



## Appendices

**List of tables and figures:**

## 1. Program Objectives

The assigned work scope includes the modification and utilization of the Plasma Converter System, Integration of a StarCell™ Multistage Ceramic Membrane System (StarCell), and testing of the integrated systems towards DOE targets for gasification and membrane separation. Testing and evaluation was performed at the Startech Engineering and Demonstration Test Center in Bristol, CT.

The Objectives of the program are as follows:

- ✓ *Characterize the performance of the integrated Plasma Converter and StarCell™ Systems for hydrogen production and purification from abundant and inexpensive feedstocks.*
- ✓ *Compare integrated hydrogen production performance to conventional technologies and DOE benchmarks.*
- ✓ *Run pressure and temperature testing to baseline StarCell's performance.*
- ✓ *Determine the effect of process contaminants on the StarCell™ system.*

## 2. Test Overview

There were three main aspects to the testing performed:

- □ Baseline characterization and adjustment/optimization of the performance of the StarCell Multistage Ceramic Membrane System,
- □ Gasification of coal and municipal solid waste (MSW) feedstocks with the Plasma Converter System (PCS), and
- □ Separation of hydrogen from the resultant gas using the StarCell.

Testing focused on process characterization to aid in determining the potential of these technologies to meet or exceed DOE cost and performance goals for hydrogen production.

Processing occurred at the Startech Plasma Converter™ Engineering Research and Demonstration Facility at 190 Century Drive, Bristol, Connecticut, USA. Startech personnel operated the system for the Program. Test data was collected via process instrumentation, online analysis, and off-site analysis. Rojac Air Testing Services, Inc, (Rojac) an Independent sampling and test company, was brought in to perform detailed gas characterization.

## 3. StarCell Gas Separation

3.1 StarCell System Description

StarCell system construction was a major accomplishment of this research effort as it is a very flexible tool for pilot scale membrane characterization in general. Instrumentation on the StarCell provides continuous process data such as temperatures, pressures, flows, and gas composition at points of interest in the purification system. StarCell was constructed to accommodate tubular membranes bundled together in modules, though planar stacks and other configurations could easily be incorporated. It also has two stages of compression to evaluate various multistage module configurations. Some of the operational configurations are as follows:

- Single stage compression cascading through multiple stages of modules
- Dual compression for instances where stage 1 permeate pressure is recompressed to drive Stage 2 separation
- Stage 1 to Stage 2 switching to allow stage 1 to stage 2 configurations of 6 and 2, 5 and 3, or 4 and 4 as conditions and membrane performance require.

**Figure 3.1: StarCell Process Flow Diagram**

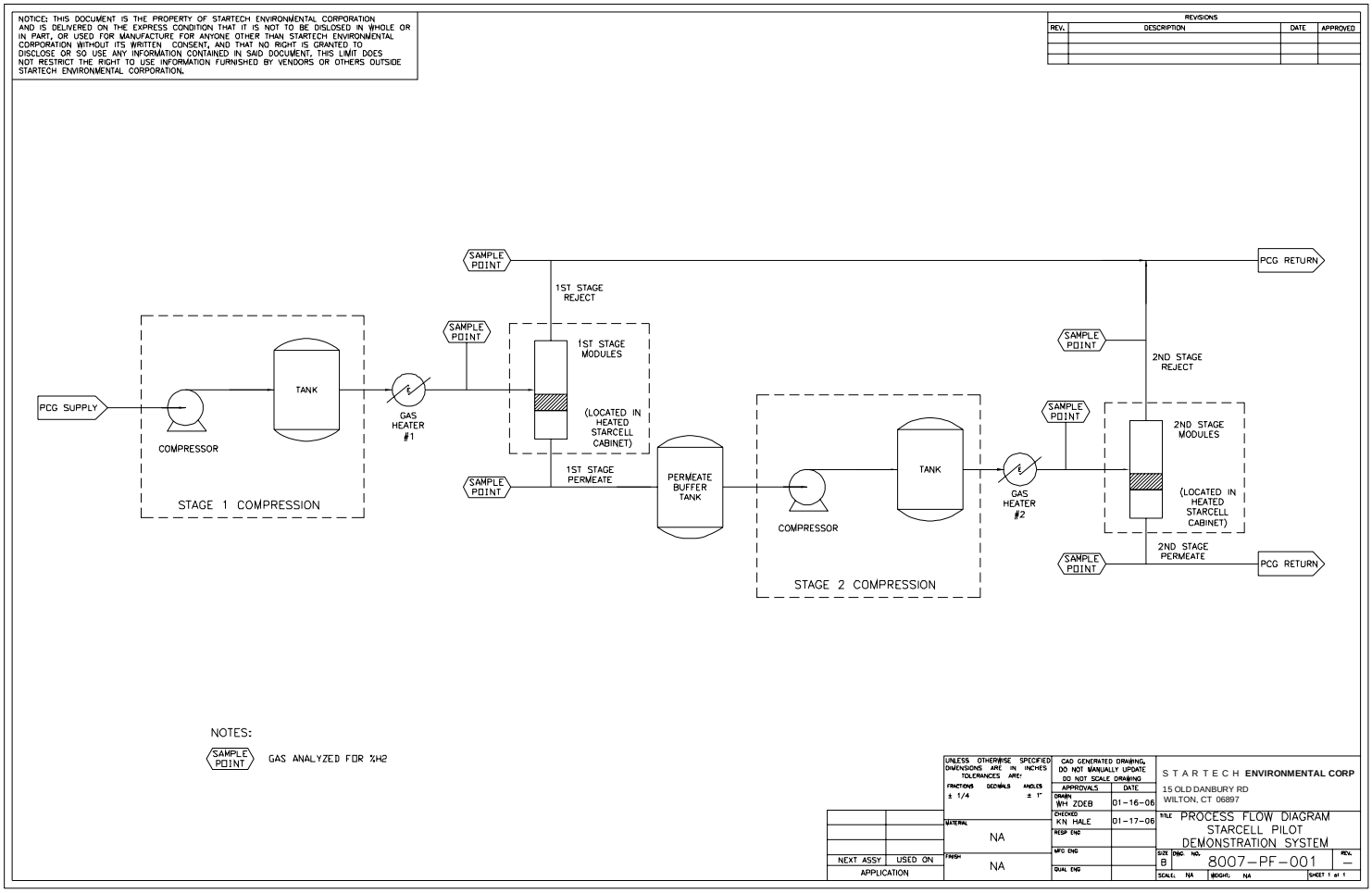


Figure 3.1 shows a Process Flow Diagram of the StarCell system. Hydrogen rich gas is fed into the stage 1 compressor. If the feed gas is already compressed, then the compressor can be bypassed. The feed gas is pressure regulated through a heat exchanger to heat the gas before flowing to the first stage of membranes for purification. The membrane housings and interconnecting piping are in a heated cabinet to prevent ambient heat loss and to keep the piping itself from cooling the gas. Gas flow through the stage 1 membranes is regulated by a needle valve on the reject side of the membranes and by the permeance of the membranes themselves. The stage 1 permeate flows to a permeate buffer tank. When the permeate buffer tank reaches a pressure set point, the stage 2 compressor pumps down the permeate buffer tank to a higher pressure tank that is used to feed stage 2 membranes. Gas flow from the higher pressure Stage 2 tank is again pressure regulated through a heat exchanger prior to introduction to the stage 2 membranes. Alternatively, the permeate buffer tank and the stage 2 compressor can be bypassed altogether allowing the permeate from stage 1 to flow directly through the heat exchanger to the stage 2 membranes.

## 3.2 StarCell Shakedown Testing

### 3.2.1 Objectives:

3.2.1.1 To characterize basic StarCell operation and responsiveness of the system using an inert gas mixture.

3.2.1.2 Compare results of StarCell System instrumentation with laboratory quality control information using Helium and Nitrogen.

3.2.1.3 Determine reasonable parametric limits to be used in optimization testing.

3.2.1.4 Develop a test worksheet to guide through system level testing to ensure that all data is obtained is captured in a consistent fashion.

### 3.2.2 Test Description:

3.2.2.1 Test Summary: During this test, an inert mixture of Helium and Nitrogen will be run through the StarCell system. Control parameters will be spanned to both verify the operability of the system subcomponents and to determine their effective range.

3.2.2.2 Data and Analysis: Data obtained from the StarCell system will include gas flows, gas temperatures, and pressures, operation times, parameter changes, and observations of the system operation. Internal analysis will be performed on the gas stream to determine helium content after Stage 1 and after Stage 2.

3.2.2.3 External Testing: The inert gas mixture will be tested for composition by a third party laboratory prior to use in the

StarCell. No additional third party analysis is required for this part of the test.

### 3.2.3 Results and Discussion:

While the shakedown test approach was very straight forward, the intent was to find out what kind of unplanned complications would arise. The testing for the gas separation portion of this research was to be performed on a first generation set of membrane modules that utilized high temperature epoxy material to pot the membrane into the module configuration. During the potting process, fumes from the epoxy had deposited themselves onto the membranes and caused a significant drop in membrane performance.

Once the system was started, we were unable to achieve the temperatures that we expected from the system. The operating temperature for the first generation of modules was limited to a maximum of 150°C (300°F) due to the epoxy resin. In order to avoid potential ignition sources in areas that may contain hydrogen, the StarCell was designed with a hot oil heating system with the capability to heat the oil to 500°F. Heat was to be transferred to the separation system via two oil-to-gas heat exchangers to heat the gas directly prior to separation. There is also a primary heat exchanger that was designed to heat the insulated cabinet that housed the membrane modules, interconnecting piping, and manifolds. Several improvements such as better pipe insulation, better cabinet insulation, and a larger oil heater improved the temperature somewhat, but the resulting temperatures were still far below the expected gas temperatures. While the StarCell cabinet temperature reached ~125°C (257°C), the steady state gas temperature going into the modules during shakedown testing averaged ~ 39°C (102°F). The average gas temperature leaving the reject side of the modules was 57°C (134°F). (See StarCell Data in Appendix A)

The lower than expected operating temperatures had negative effects on the performance of the membranes. While it was expected that the permeance of the membranes would be lower at the lower temperatures, we also observed that the permeance degraded quickly at the lower temperatures even with bottled gas mixtures. It is most probable that semi-volatile hydrocarbons from the epoxy caused the degradation of the membranes. The membranes were removed from the StarCell System and were replaced with a new set of membranes potted with a low temperature glass material.

A significant error was identified in the initial Hydrogen analyzer results. Although the system was calibrated for the specified hydrogen range prior to leaving the factory, the analyzer was yielding non-linear results for our gas analysis. This error was discovered when the system was calibrated with a 50% span gas and then a 100%

hydrogen gas read only 76% Hydrogen. The Hydrogen Analyzer was subsequently repaired and returned to service.

Parametric optimization of the StarCell system during shakedown testing is reflected in Table 3.2. Gas temperature was held at a maximum and ranged from 35°C to 45°C although the cabinet temperature was 125°C. The oil temperature was 230°C – 260°C. Stage 1 pressure was held constant at ~ 100 psig (a maximum) to allow a deadband of 100 psig – 150psig for the stage 1 compressor. The system was run in a cascade configuration such that pressure built up on the permeate side of stage 1 was also the driving pressure through stage 2. The stage 2 compressor piping and surge tanks were bypassed completely to minimize the volume of the piping from stage 1 permeate to stage 2 introduction. Data is presented in Table 3.2.

**Table 3.2: Shakedown Test; Summary of test conditions**

| **Stage 1 He and N2 separation:** | | |
|---|---|---|
| Test Gas He input: | 50% | |
| Test Gas Temperature (Reject): | 50 | °C |
| Feed pressure: | 100 | psig |
| Feed Partial Pressure He: | 50 | psi |
| Permeate Pressure: | 45 | psig |
| Permeate side gas composition (%): | 79% | |
| Permeate Partial Pressure He: | 35.6 | psi |
| H2 Partial Pressure Diff: | 14.5 | psi |
| Membrane surface area: | 0.304 | m2 |
| Total gas flow to membrane (lpm): | 1.9 | lpm |
| Total He to membrane: | 0.95 | lpm |
| Permeate gas flow: | 0.6 | lpm |
| Recovery rate: | 50% | |
| Permeance: | 0.094 | m3/m2/hr/bar |
| Flux: | 0.43 | scfh/sf |

**Table 3.2: Shakedown Test; Summary of test conditions (cont.)**

| **Stage 2 He and N2 separation:** | | |
|---|---|---|
| Test Gas He input: | 79% | |
| Test Gas Temperature (Reject): | 60 | °C |
| Feed pressure: | 100 | psig |
| Feed Partial Pressure He: | 79 | psi |
| Permeate Pressure: | 1.2 | psig |
| Permeate side gas composition (%): | 96% | |
| Permeate Partial Pressure He: | 1.2 | psi |
| H2 Partial Pressure Diff: | 77.8 | psi |
| Membrane surface area: | 0.156 | m2 |
| Total gas flow to membrane (lpm): | 2.3 | lpm |
| Total He to membrane: | 1.817 | lpm |
| Permeate gas flow: | 1.25 | lpm |
| Recovery rate: | 66% | |
| Permeance: | 0.086 | m3/m2/hr/bar |
| Flux: | 0.39 | scfh/sf |

Performance data provided to Startech Environmental Corp. on these membrane modules indicated that performance should have been better than the performance indicated above. Quality data provided by M&PT on the modules is shown in Table 3.2.

**Table 3.3: Media and Process Technology Module Quality Data**

**Permeance @ 120°C [m3/m2/hr/bar]**

| **Membrane ID** | **He** | **N2** | **H2** | **Cf** |
|---|---|---|---|---|
| ***2nd Generation*** | | | | |
| -01 | 0.29 | 0.0217 | | 0.339 |
| -02 | 0.376 | 0.039 | | 0.402 |
| -03 | 0.209 | 0.0128 | | 0.358 |
| ***3rd Generation*** | | | | |
| -05 | 0.312 | 0.00815 | 0.63 | 0.339 |

**Flux @ 30psi H2 [m3/hr]**

| **Membrane ID** | **He** | **N2** | **H2** | **He/N2** | **H2/N2** |
|---|---|---|---|---|---|
| ***2nd Generation*** | | | | | |
| -01 | 0.0924 | 0.0069 | | 13.4 | |
| -02 | 0.1010 | 0.0105 | | 9.6 | |
| -03 | 0.0631 | 0.0039 | | 16.3 | |
| ***3rd Generation*** | | | | | |
| -05 | 0.0994 | 0.0026 | 0.2007 | 38.3 | 77.3 |

There were several differences in the test set-up that clarify the differences in the results. M&PT testing was done at 120°C. While the StarCell cabinet reached temperatures of 125°C, the actual gas

temperatures and thus the actual membrane temperatures were significantly less. The other significant difference was that the M&PT data was obtained using pure component gases to obtain selectivity data where as the above data was obtained on actual gas mixtures.

*3.2.4 Hydrogen Separation Baseline Testing*

*3.2.5 Objectives*

3.2.5.1 To characterize basic StarCell operation and responsiveness of the system using a calibrated blend of Hydrogen and Carbon Monoxide.

3.2.5.2 Compare StarCell System performance with projected module performance.

3.2.5.3 Perform parametric testing to dial in optimal settings for hydrogen separation from CO.

3.2.5.4 Determine baseline system characteristics (i.e. Hydrogen recovery rate, system capacity, purity capability, multistage effectiveness)

*3.2.6 Test Description:*

3.2.6.1 Test Summary: During this test, a mixture of Hydrogen and Carbon Monoxide will be run through the StarCell system. Control parameters will be tuned to determine optimal separation conditions within the StarCell System.

3.2.6.2 Data and Analysis: Data obtained from the StarCell system will include gas flows, gas temperatures, and pressures, operation times, parameter changes, and observations of the system operation. Internal analysis will be performed on the gas stream to determine helium content after Stage 1 and after Stage 2.

3.2.6.3 External Testing: Gas mixtures will be tested for composition by a third party laboratory prior to use in the StarCell. No additional third party analysis is required.

*3.2.7 Results and Discussion:*

Initial Hydrogen separation testing was performed under the same conditions as the shakedown testing with the exception that the stage 2 compressor was enabled. This changed the pressure differential for both stage 1 and stage 2. The results are summarized in Tables 3.3 and 3.4:

**Table 3.4: Stage 1 H2 and CO separation**

| **Stage 1 H2 and CO separation:** | | |
|---|---|---|
| Test Gas H2 input: | 50% | |
| Test Gas Temperature (Reject): | 50 | °C |
| Feed pressure: | 102 | psig |
| Feed Partial Pressure H2: | 51 | psi |
| Permeate Pressure: | 7 | psig |
| Permeate side gas composition (%): | 80% | |
| Permeate Partial Pressure H2: | 5.6 | psi |
| H2 Partial Pressure Diff: | 45.4 | psi |
| Membrane surface area: | 0.304 | m2 |
| Total gas flow to membrane (lpm): | 5.6 | lpm |
| Total H2 to membrane: | 2.8 | lpm |
| Permeate gas flow: | 2.8 | lpm |
| Recovery rate: | 80% | |
| Permeance: | 0.141 | m3/m2/hr/bar |
| Flux*: | 0.64 | scfh/sf |

**Table 3.5: Stage 2 H2 and CO separation**

| **Stage 2 H2 and CO separation:** | | |
|---|---|---|
| Test Gas H2 input: | 80% | |
| Test Gas Temperature (Reject): | 60 | °C |
| Feed pressure: | 100 | psig |
| Feed Partial Pressure H2: | 80 | psi |
| Permeate Pressure: | 1.2 | psig |
| Permeate side gas composition (%): | 96% | |
| Permeate Partial Pressure H2: | 1.2 | psi |
| H2 Partial Pressure Diff: | 78.8 | psi |
| Membrane surface area: | 0.156 | m2 |
| Total gas flow to membrane (lpm): | 2.3 | lpm |
| Total H2 to membrane: | 1.84 | lpm |
| Permeate gas flow: | 1.25 | lpm |
| Recovery rate: | 65% | |
| Permeance: | 0.085 | m3/m2/hr/bar |
| Flux*: | 0.38 | scfh/sf |

* Flux corrected to 20 psi hydrogen partial pressure differential. No correction has been made for temperature which is supposed to be at 400°C for DOE target flux rate.

Membrane performance particularly on the stage 1 modules was better when using hydrogen than when using helium. Through optimization of reject settings, recovery rates can likely be improved.

A battery of tests was performed on the membranes using pure component gases to reproduce the M&PT quality tests reported to us. Four modules were provided for testing, but Module 2 was found to be leaking during initial testing and was removed from service. Damage may have occurred during shipment.

**Table 3.6: Pure Component Test; Module 1**

| **Module 1: Stage 1** | **Nitrogen** | | **Hydrogen** | |
|---|---|---|---|---|
| Test Gas input: | 100% | | 100% | |
| Test Gas Temperature (Reject): | 50 | °C | 40 | °C |
| Feed pressure: | 101 | psig | 97 | psig |
| Feed Gas Partial Pressure: | 101 | psi | 97 | psi |
| Permeate Pressure: | 0.1 | psig | 0.3 | psig |
| Permeate gas composition (%): | 100% | | 100% | |
| Permeate Partial Pressure: | 0.1 | psi | 0.3 | psi |
| Partial Pressure Diff: | 100.9 | psi | 96.7 | psi |
| Membrane surface area: | 0.156 | m2 | 0.156 | m2 |
| Total gas flow to membrane (lpm): | 1.18 | lpm | 6.2 | lpm |
| Total Interest to membrane: | 1.18 | lpm | 6.2 | lpm |
| Permeate gas flow: | 0.48 | lpm | 5.3 | lpm |
| Recovery rate: | 41% | | 85% | |
| Permeance: | 0.027 | m3/m2/hr/bar | 0.306 | m3/m2/hr/bar |
| Module Selectivity (H2 / N2 perm): | 11.5 | scfh/sf | | |

**Table 3.7: Pure Component Test; Module 3**

| **Module 3: Stage 1** | **Nitrogen** | | **Hydrogen** | |
|---|---|---|---|---|
| Test Gas input: | 100% | | 100% | |
| Test Gas Temperature (Reject): | 50 | °C | 46 | °C |
| Feed pressure: | 100 | psig | 99.5 | psig |
| Feed Gas Partial Pressure: | 100 | psi | 99.5 | psi |
| Permeate Pressure: | 0.1 | psig | 0.1 | psig |
| Permeate gas composition (%): | 100% | | 100% | |
| Permeate Partial Pressure: | 0.1 | psi | 0.1 | psi |
| Partial Pressure Diff: | 99.9 | psi | 99.4 | psi |
| Membrane surface area: | 0.148 | m2 | 0.148 | m2 |
| Total gas flow to membrane (lpm): | 1.2 | lpm | 5.05 | lpm |
| Total Interest to membrane: | 1.2 | lpm | 5.05 | lpm |
| Permeate gas flow: | 0.4 | lpm | 4.25 | lpm |
| Recovery rate: | 33% | | 84% | |
| Permeance: | 0.024 | m3/m2/hr/bar | 0.251 | m3/m2/hr/bar |
| Module Selectivity (H2 perm / N2 perm): | 10.7 | | | |

**Table 3.8: Pure Component Test; Module 4**

| Module 4: Stage 2 | Nitrogen | | Hydrogen | |
|---|---|---|---|---|
| Test Gas input: | 100% | | 100% | |
| Test Gas Temperature (Reject): | 62 | °C | 58 | °C |
| Feed pressure: | 100 | psig | 98.5 | psig |
| Feed Gas Partial Pressure: | 100 | psi | 98.5 | psi |
| Permeate Pressure: | 0.1 | psig | 0.2 | psig |
| Permeate gas composition (%): | 100% | | 100% | |
| Permeate Partial Pressure: | 0.1 | psi | 0.2 | psi |
| Partial Pressure Diff: | 99.9 | psi | 98.3 | psi |
| Membrane surface area: | 0.156 | m2 | 0.156 | m2 |
| Total gas flow to membrane (lpm): | 1.17 | lpm | 4.83 | lpm |
| Total Interest gas to membrane: | 1.17 | lpm | 4.83 | lpm |
| Permeate gas flow: | 0.13 | lpm | 3.47 | lpm |
| Recovery rate: | 11% | | 72% | |
| Permeance: | 0.007 | m3/m2/hr/bar | 0.197 | m3/m2/hr/bar |
| Flux: | 0.03 | scfh/sf | 0.89 | scfh/sf |
| Module Selectivity (H2 perm / N2 perm): | 27.1 | | | |

The pure component verification yielded permeance results that ranged from 1/3 to ½ the reported results in the quality tests. The results indicate that the membrane modules were performing comparably in the StarCell system as in the laboratory. It also shows that the second generation (Modules 1 and 3) and third generation membranes (Module 4) did not degrade significantly during testing like the first generation membranes did. The lower permeance measurements are a direct result of the lower operating temperature of the StarCell system.

# 4 Plasma Converter System Gas Generation

## *4.1 PCS Coal Gas characterization*

### *4.1.1 Objectives*

4.1.1.1 To characterize gas produced by the Plasma Converter System while processing coal

4.1.1.2 To identify areas for improvement from a processing or from an efficiency standpoint.

4.1.1.3 To compare the gas produced from the Plasma converter with the gas produced by other coal gasification technologies.

### *4.1.2 Test Description:*

4.1.2.1 Test Summary: During this test, coal will be fed to the Plasma Converter System and the gas produced from the system will be sampled and analyzed by third party sampling and test agencies.

4.1.2.2 Data and Analysis: Data auto-acquisitioned from the Plasma Converter System will include gas flows, gas temperatures, pressures, gas composition and other process information. Manual data will include operation times, actual feed, parameter changes, data that is not being automatically recorded, and observations of the system operation. Online hydrogen analyzers will be used to provide real time hydrogen composition of the gas exiting the Plasma Converter.

4.1.2.3 External Testing: An Independent sampling company will perform the bulk of the gas sampling and will coordinate outside analysis directly. Table 4.1 shows a sample matrix describing the parameter to be tested, the analytical method, and the number of samples to be analyzed for that material during the test.

**Table 4.1: Coal Gas sampling Matrix**

| *Test Parameter* | *Test Method* | *Number of Tests* |
|---|---|---|
| *Siloxanes* | *Method TO-15* | *3* |
| *Mercaptans* | *Method TO-15* | *3* |
| *Heavy Metals* (Ag, As, Ba, Cd, Cr, Hg, Pb, Se) | *EPA M29* | *3* |
| *SO2, SO3* | *EPA M8* | *3* |
| *CO, CO2, CH4, N2, O2* | *ASTM1845* | *3* |
| *H2* | *GC TCD / Argon Carrier* | *3* |
| *Dioxin / Furan* | *EPA M23* | *1* |
| *SVOC* | *EPA M0010* | *1* |
| *Hydrogen Cyanide* | *EPA M033* | *3* |
| *Hydrogen Sulfide* | *ASTM D5504* | *3* |
| *Oxides of Nitrogen* | *EPA M7E* | *3* |
| *O2 /CO2* | *EPA M3A* | *3* |
| *ISO Kinetic Particulate Sampling* | *EPA Method 5* | *3* |
| *HCL / CL2* | *EPA Method 26A Modified ** | *3* |
| *Ammonia* | | *3* |

### *4.1.3 Results and Discussion*

#### 4.1.3.1 Coal Physical Characteristics

The coal used in this testing was pure anthracite coal sized as "pea" coal. This material has been screened to be less than ¾ of an inch. No further preprocessing of the coal was performed. The bulk density was measured by placing a sample of the coal into a tared container, weighing it, and dividing the weight of the material by the volume of the container. The true density of the coal was also measured by placing a sample in a graduated cylinder ½ full of water.

**Table 4.2 Coal Density**

| Characteristic | Result (g/cc) |
|---|---|
| Bulk Density | 0.866 |
| Actual Density | 1.558 |

#### 4.1.3.2 Coal Chemical Characteristics

A compositional analysis was performed on the coal. The results are shown in table 4.2.

**Table 4.3: Coal Chemical Composition**

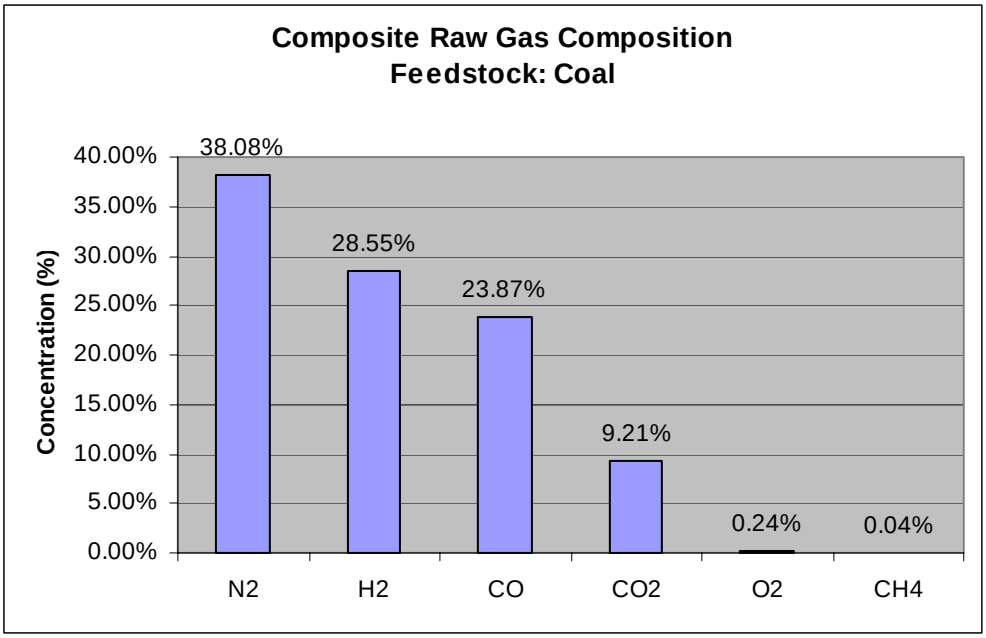
| Parameter | | Results | | MDL | Method | Analyzed/Time | Tech |
|---|---|---|---|---|---|---|---|
| Ag-Silver Total | < | 10 | mg/kg | 10 | SW 846 6010B | 9/9/2005 | dfp |
| As-Arsenic Total | < | 0.5 | mg/kg | 0.5 | Sw 846 7060A | 9/14/2005 | dfp |
| Ba-Barium Total | | 53.9 | mg/kg | 50 | SW 846 6010B | 9/9/2005 | dfp |
| Cd-Cadmium Total | < | 1 | mg/kg | 1 | SW 846 6010B | 9/9/2005 | dfp |
| Cr-Chromium Total | | 51.2 | mg/kg | 5 | SW 846 6010B | 9/9/2005 | dfp |
| Hg-Mercury Total | | 137 | ug/kg | 50 | SW 846 7471A | 9/19/2005 | dfp |
| Pb-Lead Total | | 28.5 | mg/kg | 5 | SW 846 7421 | 9/9/2005 | dfp |
| Se-Selenium Total | < | 0.5 | mg/kg | 0.5 | SW 846 7740 | 9/14/2005 | dfp |
| Ash,% | | 10.2 | | 0.05 | ASTM D-3174 | 9/15/2005 | |
| Carbon,% | | 65 | | 1 | ASTM D-5373 | 9/7/2005 | |
| Hydrogen,% | | 2.09 | | 0.1 | ASTM D-5373 | 9/7/2005 | |
| Nitrogen,% | | 0.66 | | 0.1 | ASTM D-5373 | 9/7/2005 | |
| Oxygen,% | | 21.44 | | 0.1 | | 9/7/2005 | |
| Sulfur, % | | 0.61 | | 0.2 | ASTM D-4239 | 9/6/2005 | |

The carbon and oxygen results reported for the composition of coal were questionable as anthracite coal typically contains 92 – 98% Carbon. The results clearly indicate; however, that there was significant lead, mercury, chromium, and barium in the coal for heavy metals, as well as significant amounts of sulfur.

*4.1.3.3 PCG synthesis gas characterization*

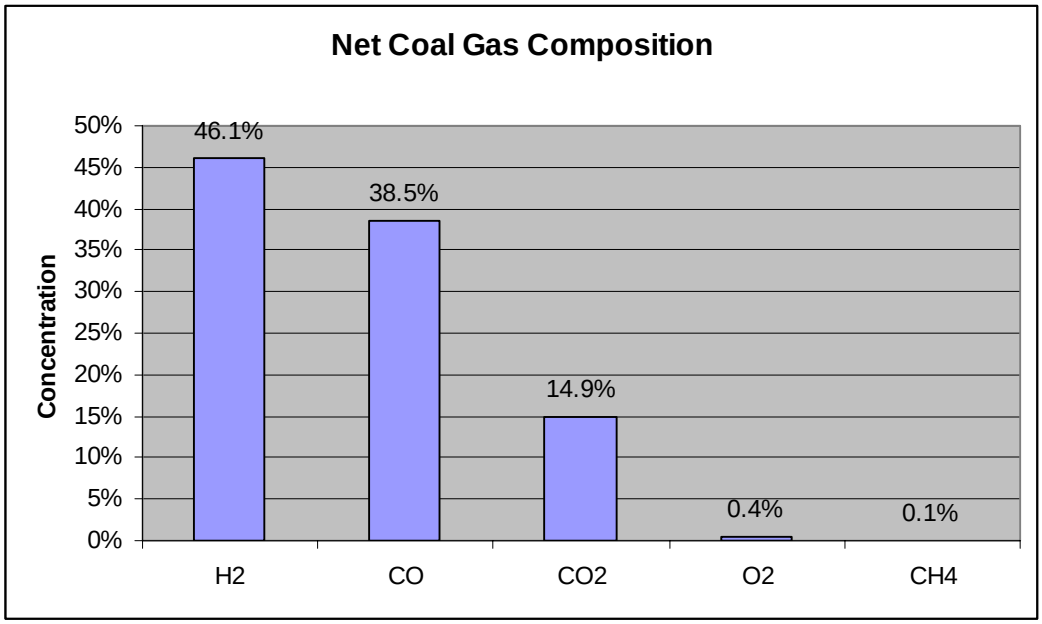
The data collected during testing was extensive. The composition of the gas was measured with Startech continuous monitoring equipment, Rojac's continuous monitoring equipment, and grab samples obtained during the test and sent to independent labs for verification. The composition of the raw PCG gas from the test is shown in Figure 4.4. The data in the graph represents a composite of Startech data, Rojac continuous monitoring data, and laboratory results.

**Figure 4.4: Composite Gas Composition for Coal**




Nitrogen for this testing was much higher than would be normal for a commercial PCS due to the type of torch used in the testing. Another contributor to the high nitrogen content was nitrogen that leaked into the system primarily through the feed system. Based on nitrogen flow tests done without feed, all of the nitrogen measured in the PCG can be accounted for with equivalent contributions from the torch and from air leakage. Again this is not representative of the a commercial type feed system as there was no seal such as a rotary valve used to isolate the feed auger from the plasma vessel. We have also observed that when processing coal, air leakage into the system has a tendency to preferentially lead to the formation of CO2 and soot rather than CO. The gas composition without nitrogen contributed by the torch and leakage is shown in Table 4.5

**Figure 4.5: Net Gas Composition for Coal**




The gas composition measured was what would be expected of a coal-based synthesis gas without water gas shift. The high nitrogen content made this particular gas less than ideal for hydrogen purification, but the nitrogen content can be easily reduced in a commercial system by using a torch that uses less or no nitrogen, and by incorporating more absolute sealing systems on the Plasma Converter System to prevent ambient air from leaking into the system.

*4.1.3.4 Contaminant analysis*

Additional testing was performed by the independent sampling company and independent labs to determine the concentration of low level contaminants that are produced during gasification. Determining what these contaminants might be and how they affect the hydrogen purification process are key aspects of this research. A detailed summary of the gas and contaminant data can be found in Appendix C. For discussion purposes, the results will be compared to emission limits. It is important to note that the gas generated and even the reject gas from hydrogen purification should never be emitted directly to the atmosphere, but is designed to be used as a fuel or as a raw material in additional industrial processes. When the gas is used, it is diluted significantly, and organics are typically destroyed. This means that if the Plasma Converted Gas (PCG) itself meets emission requirements, then the actual emission when the fuel is used will have extraordinary environmental performance.

**Table 4.6: Summary of Coal Gas Contaminant Analysis**

| Test Parameter | Results description |
|---|---|
| Siloxanes, HAP | Very Low. Almost all below the detection limit. A couple detected but near detection limit. CS2~77 ug/dscm, Flyer hit for Acetone. |
| Mercaptans | None Detected |
| Heavy Metals (Ag, As, Ba, Cd, Cr, Hg, Pb, Se) | All metals were either in the non-detect or ug / dscm range (very low). Metals of particular concern with coal: Hg 0.8 ug/dcsm, Pb 3.9 ug/dscm, Cr 2.0 ug/dscm, Cd 0.2 ug/dscm, Ba None detected. |
| SO2, SO3 | None detected |
| CO, CO2, CH4, N2, O2 | See section 4.1.3.3 |
| H2 | See section 4.1.3.3 |
| Permanent Gases | Almost no non-methane hydrocarbons. Very good for membrane performance. 470 ppm CH4, ~5 ppm of Acetylene and Ethene, Non detect on all others. |
| Dioxin / Furan | Very Low, 0.005 ng/dscm CDD TEF, 0.002 ng/dscm CDF TEF |
| SVOC | Very Low, Almost all non-detects. |
| Hydrogen Cyanide | None Detected |
| Hydrogen Sulfide | None Detected |
| Oxides of Nitrogen | Avg. 190 ppm |
| O2 /CO2 | See section 4.1.3.3 |
| ISO Kinetic Particulate Sampling | Extremely Low; 0.3 mg/dscm. Very Good for membrane performance |
| HCL / CL2 | None detected |
| Ammonia | None detected |

The environmental performance of the Plasma Converter System was excellent. It was able to produce a clean synthesis gas from coal that was very low in contaminants and other hazardous byproducts.

## 4.2 Municipal Solid Waste Gas Characterization

*4.2.1 Objectives*

4.2.1.1 To characterize gas produced by the Plasma Converter System while processing a simulated Municipal Solid Waste

4.2.1.2 To identify areas for improvement from a processing or from an efficiency standpoint.

4.2.1.3 To compare the gas produced from the Plasma converter with the gas produced by other gasification technologies.

4.2.1.4 To determine operating parameters to be used for generating hydrogen rich gas for subsequent purification.

*4.2.2 Test Description:*

4.2.2.1 Test Summary: During this test, a surrogate municipal solid waste was fed to the Plasma Converter System and the gas produced from the system was sampled and analyzed by third party sampling and test agencies. The operating conditions run for this test were documented and used to produce hydrogen rich gas to be purified in the StarCell System.

4.2.2.2 Data and Analysis: Data auto-acquisitioned from the Plasma Converter System included gas flows, gas temperatures, pressures, gas composition and other process information. Manual data includes operation times, actual feed, parameter changes, data that is not being automatically recorded, and observations of the system operation. Online hydrogen analyzers will be used to provide real time hydrogen composition of the gas exiting the Plasma Converter.

4.2.2.3 External Testing: Rojac Air Testing Services Inc performed the bulk of the gas sampling and arranged outside analysis directly. Table 4.7 shows a sample matrix describing the parameters tested, the analytical method, and the number of samples analyzed for that material during the test.

**Table 4.7: MSW Gas sampling Matrix**

| Test Parameter | Test Method | Number of Tests |
|---|---|---|
| Siloxanes | Method TO-15 | 3 |
| Mercaptans | Method TO-15 | 3 |
| Heavy Metals (Ag, As, Ba, Cd, Cr, Hg, Pb, Se) | EPA M29 | 3 |
| SO2, SO3 | EPA M8 | 3 |
| CO, CO2, CH4, N2, O2 | ASTM1845 | 8 |
| H2 | GC TCD / Argon Carrier | 3 |
| Dioxin / Furan | EPA M23 | 3 |
| SVOC | EPA M0010 | 3 |
| Hydrogen Cyanide | EPA M033 | 3 |
| Hydrogen Sulfide | ASTM D5504 | 3 |
| Oxides of Nitrogen | EPA M7E | 3 |
| O2 /CO2 | EPA M3A | 3 |
| ISO Kinetic Particulate Sampling | EPA Method 5 | 3 |
| HCL / CL2 | EPA Method 26A Modified * | 3 |
| Ammonia | | 3 |

### 4.2.3 Results and Discussion

#### 4.2.3.1 MSW Feedstock Characteristics

A surrogate MSW was made for this testing based on 2003 EPA data on MSW composition after recycling. Table 4.8 shows the EPA data on municipal solid waste composition both before and after recycling.

**Table 4.8: 2003 MSW Composition Before and After Recycling**

| | Raw Composition | MMTons | Mass Post Recycling | Adjusted MM Tons | % Post Recycle |
|---|---|---|---|---|---|
| Paper: | 35.2% | 83.1 | 74.7 | 74.7 | 43.6% |
| Yard Trimmings: | 12.1% | 28.6 | 18.8 | 18.8 | 10.9% |
| Food Scraps: | 11.7% | 27.6 | 27.6 | 27.6 | 16.1% |
| Plastics: | 11.3% | 26.7 | 16.7 | 16.7 | 9.8% |
| Metals: | 8.0% | 18.9 | 0.8 | 0.0 | 0.0% |
| Rubber, Leather, and Textiles: | 7.4% | 17.5 | 11.3 | 11.3 | 6.6% |
| Glass: | 5.3% | 12.5 | 8.7 | 8.7 | 5.1% |
| Wood: | 5.8% | 13.7 | 13.7 | 13.7 | 8.0% |
| Other: | 3.4% | 8.0 | 8.0 | 0.0 | 0.0% |
| | 100% | 236 | 180 | 171.5 | 100.0% |

Data Source: http://www.epa.gov/epaoswer/non-hw/muncpl/facts.htm

During trial runs, there was difficulty getting a consistent feed using the MSW surrogate due to bridging of the feedstock in the auger feeder. The cause of the bridging was the recycled paper, fibrous wood and hay used for yard trimmings. After several waste formula changes, the paper, wood, and yard trimmings had to be replaced with wood pellets to maintain a chemical composition as close as possible with the documented municipal solid waste composition. The waste formula used during the testing is shown in Table 4.9.

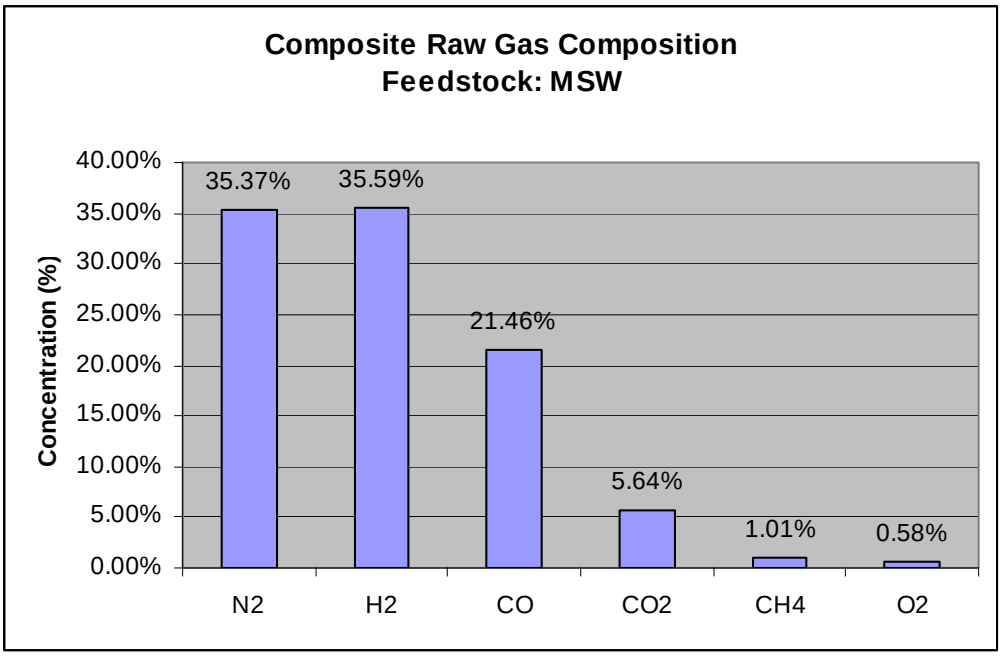
**Table 4.9: Municipal Solid Waste Feedstock Composition**

| MSW Feedstock Composition: | Composition | Surrogate Component |
|---|---|---|
| Paper: | 44% | Wood Pellets |
| Yard Trimmings: | 11% | Wood Pellets |
| Food Scraps: | 16% | Potatoes |
| Plastics: | 10% | Mixed Plastic |
| Metals: | 0% | |
| Rubber, Leather, and Textiles: | 7% | Shredded Tires |
| Glass: | 5% | Broken Glass |
| Wood: | 8% | Wood Pellets |

*4.2.3.2 PCS MSW Gas characterization*

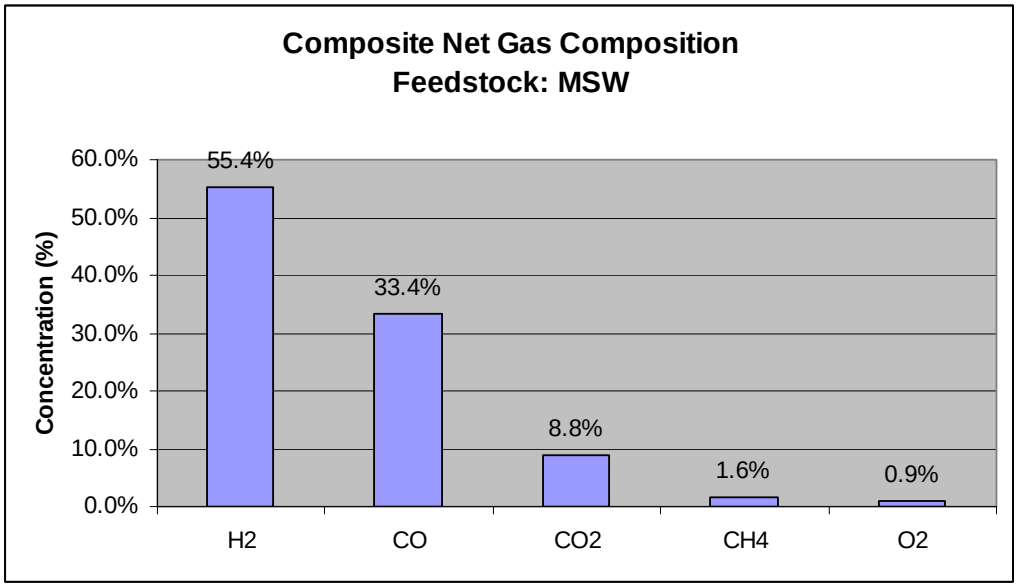
The composition of the gas was measured with Startech continuous monitoring equipment, Rojac's continuous monitoring equipment, and grab samples obtained during the test and sent to independent labs for verification. The composition of the raw PCG gas from the MSW test is shown in Figure 4.9. The data in the graph represents a composite of Startech data, Rojac continuous monitoring data, and Laboratory results. For this testing, there were 8 bag samples taken for gas composition by Rojac and sent to two different labs for analysis.

**Figure 4.10: Composite Gas Composition for MSW**




The composition of the gas generated from the MSW was better than the gas generated by the coal. The hydrogen content was higher as the MSW feedstock inherently has more hydrogen in it than the coal. Both the N2 and the CO2 were lower for this gas indicating that there was less air leakage into the system relative to the gas flow which was higher for the MSW runs. Again the all of the nitrogen found in the gas can be attributed to the nitrogen from the torch and nitrogen from leakage into the vessel. Figure 4.10 shows the adjusted gas composition from MSW without nitrogen.

**Figure 4.11: Net Gas Composition for MSW**




*4.2.3.3 Contaminant Analysis*

Additional testing was performed by the independent sampling company and independent labs to determine the concentration of low level contaminants that are produced during gasification. Determining what these contaminants might be and how they affect the hydrogen purification process are key aspects of this research. A detailed summary of the gas and contaminant data for the MSW runs can be found in Appendix D. For discussion purposes, the results will be compared to emission limits. It is important to note that the gas generated and even the reject gas from hydrogen purification should never be emitted directly to the atmosphere, but is designed to be used as a fuel or as a raw material in additional industrial processes. When the gas is used, it is diluted significantly, and organics are typically destroyed. This means that if the PCG itself meets emission requirements, then the actual emission when the fuel is used will have extraordinary environmental performance.

**Table 4.12: Summary of MSW Gas Contaminant Analysis**

| Test Parameter | Results description |
|---|---|
| Siloxanes, HAP | Very Low to none detected on all. CS2 7.9 mg/dscm. |
| Mercaptans | None Detected for Mercaptan and all sulfur compounds except COS 22 mg/dscm and CS2 0.004 mg/dscm |
| Heavy Metals (Ag, As, Ba, Cd, Cr, Hg, Pb, Se) | All metals were either in the non-detect or ug / dscm range (very low). Metals of particular concern with coal: Hg 0.2 ug/dcsm, Pb 1.2 ug/dscm, Cr 3.2 ug/dscm, Cd 0.2 ug/dscm, Ba None detected. |
| SO2, SO3 | None Detected |
| CO, CO2, CH4, N2, O2 | See section 4.2.3.2 |
| H2 | See section 4.2.3.2 |
| Permanent Gases | No non-methane hydrocarbons detected. Very good for membrane performance. ~1% CH4. |
| Dioxin / Furan | Very Low, 0.0035 ng/dscm CDD TEF, 0.0045 ng/dscm CDF TEF |
| SVOC | Very low. Non Detect on all except the following: 2 methylphenol 0.004 mg/dscm, Benzoic Acid 0.027 mg/dscm, Benzyl Alcohol 0.159 mg/dscm, Bis(2ethylhexyl)phthalate 0.007 mg/dscm, Naphthalene 0.006 mg/dscm |
| Hydrogen Cyanide | 5 mg/dscm |
| Hydrogen Sulfide | None Detected |
| Oxides of Nitrogen | 221 ppm dry |
| O2 /CO2 | See section 4.2.3.2 |
| ISO Kinetic Particulate Sampling | Extremely Low; 0.4 mg/dscm. Very Good for membrane performance |
| HCL / CL2 | None Detected |
| Ammonia | None Detected |

The environmental performance of the Plasma Converter System was excellent. It was able to produce a clean synthesis gas from an Municipal solid waste stimulant feedstock that was very low in contaminants and other hazardous byproducts.

## 5.0 Integrated Gasification and Hydrogen Purification

5.1 Objectives:

5.1.1 To characterize StarCell operation using Plasma converted gas generated from a municipal solid waste surrogate

5.1.2 Compare StarCell System performance on Plasma Converter synthesis gas with laboratory test data and previous results obtained using bottled gases.

5.1.3 Determine if StarCell membrane modules are affected by low level contaminants in the synthesis gas.

5.2 Test Description:

5.2.1 Test Summary: During this test, Plasma Converter Synthesis Gas will be generated by the Plasma Converter System and will then be run through the StarCell Hydrogen Purification System. These systems will be run concurrently. Results of the test will be compared with previous data to evaluate membrane module performance using actual synthesis gas

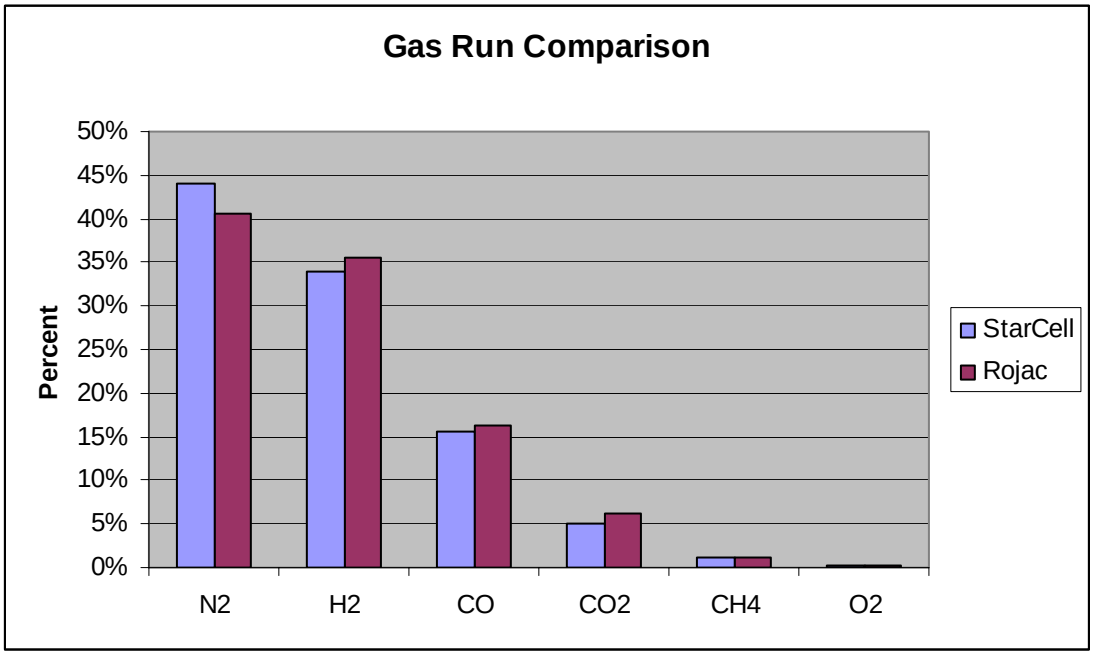
5.2.2 Data and Analysis: Data obtained from the Plasma Converter System will be primarily gas composition data. System operating conditions will be the same as during the independent lab gas analysis detailed in section 4.2. Data obtained from the StarCell system will include gas flows, gas temperatures, and pressures, operation times, parameter changes, and observations of the system operation. Internal analysis will be performed on the gas stream to determine hydrogen content after Stage 1 and after Stage 2.

5.2.3 External Testing: Gas mixtures used for instrument calibration are analyzed and certified by third party laboratories. No additional third party analysis is required.

## 5.3 Results and Discussion:

Performance of the plasma converter was almost exactly the same as it was during the detailed gas characterization runs. As a quick comparison, Figure 5.1 shows average Startech raw data averages for both the Rojac gas characterization test runs and the StarCell test runs without any normalization or correction. It should be noted that the actual gas composition was likely closer to what was reported in Figure 4.9. Startech CO read 7 – 9 % below laboratory reported levels in all permanent gas results. As Nitrogen is determined by difference, the higher CO composition drops the estimated N2 to ~ 35%.

**Figure 5.1: Gas Run Comparison**




StarCell testing was performed directly on the PCG as it was generated from the system. Conditions were almost identical to the H2 CO tests that were done during shakedown testing with the exception that the PCG had a 35% H2 content instead of a 50% H2 content as tested. The balance gas was a blend of H2, CO, CO2, and other trace gases rather than just CO. The results of the separation testing for the bottled gas and the PCG were essentially identical with calculated fluxes at 0.63 ft3/ft2. Increasing the operating temperature of the StarCell system will significantly improve the flux results.

**Table 5.2: Stage 1 StarCell Separation Results**

| | 11/30/2005 | | 12/1/2005 | |
|---|---|---|---|---|
| Test Gas H2 input: | 35% | % | 35% | % |
| Test Gas Temperature (Reject): | 45 | °C | 48 | °C |
| Feed pressure: | 102 | psig | 100 | psig |
| Feed Partial Pressure H2: | 35.7 | psi | 35 | psi |
| Permeate Pressure: | 7.5 | psig | 8.6 | psig |
| Permeate side gas composition (%): | 65% | % | 63% | % |
| Permeate Partial Pressure H2: | 4.875 | psi | 5.4 | psi |
| H2 Partial Pressure Diff: | 30.825 | psi | 29.6 | psi |
| Membrane surface area: | 0.304 | m2 | 0.304 | m2 |
| Total gas flow to membrane (lpm): | 4.8 | lpm | 4.8 | lpm |
| Total H2 to membrane: | 1.68 | lpm | 1.68 | lpm |
| Permeate gas flow: | 1.5 | lpm | 1.5 | lpm |
| Recovery rate: | 58% | | 56% | |
| Permeance: | 0.139 | m3/m2/hr/bar | 0.145 | m3/m2/hr/bar |
| Flux: | 0.63 | scfh/sf | 0.66 | scfh/sf |

The data reported in Table 5.2 was not in any way optimized for recovery. Control parameters were set in advance of the testing with reject gas flow from the membrane set at 3.3 lpm and the input pressure @ ~100 psig.

**Table 5.3: Recovery Optimization**

| | | | |
|---|---|---|---|
| Reject Flow Rate: | 0.5 | 1.0 | lpm |
| Test Gas H2 input: | 35% | 35% | % |
| Test Gas Temperature (Reject): | 29 | 35 | °C |
| Feed pressure: | 100 | 100 | psig |
| Feed Partial Pressure H2: | 35 | 35 | psi |
| Permeate Pressure: | 6.3 | 6.6 | psig |
| Permeate side gas composition (%): | 54% | 57% | % |
| Permeate Partial Pressure H2: | 3.4 | 3.8 | psi |
| H2 Partial Pressure Diff: | 31.6 | 31.2 | psi |
| Membrane surface area: | 0.46 | 0.46 | m2 |
| Total gas flow to membrane (lpm): | 1.87 | 2.3 | lpm |
| Total H2 to membrane: | 0.65 | 0.81 | lpm |
| Permeate gas flow: | 1.37 | 1.37 | lpm |
| Recovery rate: | 113% | 97% | |
| Permeance: | 0.082 | 0.083 | m3/m2/hr/bar |
| Flux: | 0.37 | 0.38 | scfh/sf |

**Table 5.3: Recovery Optimization (cont.)**

| | | | |
|---|---|---|---|
| Reject Flow Rate: | 1.5 | 2.0 | lpm |
| Test Gas H2 input: | 35% | 35% | % |
| Test Gas Temperature (Reject): | 36.5 | 40 | °C |
| Feed pressure: | 99.3 | 100.3 | psig |
| Feed Partial Pressure H2: | 35 | 35 | psi |
| Permeate Pressure: | 8.8 | 7.3 | psig |
| Permeate side gas composition (%): | 60% | 62% | % |
| Permeate Partial Pressure H2: | 5.3 | 4.5 | psi |
| H2 Partial Pressure Diff: | 29.5 | 30.6 | psi |
| Membrane surface area: | 0.46 | 0.46 | m2 |
| Total gas flow to membrane (lpm): | 2.95 | 3.53 | lpm |
| Total H2 to membrane: | 1.03 | 1.24 | lpm |
| Permeate gas flow: | 1.45 | 1.53 | lpm |
| Recovery rate: | 84% | 77% | |
| Permeance: | 0.093 | 0.095 | m3/m2/hr/bar |
| Flux: | 0.42 | 0.43 | scfh/sf |

Part of the testing performed on MSW feed was to optimize hydrogen recovery by restricting flow through the reject side of the membrane. For the recovery optimization testing, all 3 membrane modules were configured as part of stage 1 hydrogen purification. As expected, recovery increased significantly by restricting the flow of tail gas from the reject side of the membranes. However, flux and permeate quality both suffered as a result of the higher recovery rate. There are several factors that contributed to lower flux readings during this testing. Firstly, the temperature was lower for this round of testing than in previous tests. There is also an issue with mass flow in that there is less hydrogen available to go through the membrane as there is less feed-gas being introduced to the membrane. The third factor is that the membranes were steeped in the Plasma Converted Gas under pressure for ~1000 hours of exposure time since the last round of testing.

Two stage purification commenced when the stage 2 feed tank containing the compressed permeate from stage 1 reached > 100psig. At this point, Module #4 was revalved into a stage 2 configuration to allow the compressed permeate from stage 1. Two-stage purification continued under the conditions reported in Table 5.4.

**Table 5.4: Two-Stage Hydrogen Purification of PCG**

| | Stage 1 | Stage 2 | Stage 2 | |
|---|---|---|---|---|
| Test Gas H2 input: | 35% | 52% | 52% | % |
| Test Gas Temperature (Reject): | 33.5 | 37.3 | 38 | °C |
| Feed pressure: | 101 | 84.2 | 85.2 | psig |
| Feed Partial Pressure H2: | 35.4 | 43.8 | 44.3 | psi |
| Permeate Pressure: | 8.0 | 15.4 | 12.8 | psig |
| Permeate side gas composition (%): | 59% | 79% | 77% | % |
| Permeate Partial Pressure H2: | 4.72 | 12.2 | 9.9 | psi |
| H2 Partial Pressure Diff: | 30.63 | 31.6 | 34.4 | psi |
| Membrane surface area: | 0.304 | 0.156 | 0.156 | m2 |
| Total gas flow to membrane (lpm): | 2.5 | 1.0 | 0.4 | lpm |
| Total H2 to membrane: | 0.88 | 0.52 | 0.21 | lpm |
| Permeate gas flow: | 1.27 | 0.23 | 0.18 | lpm |
| Recovery rate: | 86% | 35% | 65% | |
| Permeance: | 0.119 | 0.041 | 0.029 | m3/m2/hr/bar |
| Flux: | 0.54 | 0.18 | 0.13 | scfh/sf |

Note: Stage 2 feedgas was rechecked prior to introduction to the stage 2 membrane. The hydrogen content was measured at 52% rather than the 59 – 63% hydrogen content that was measured directly from the stage 1 permeate. This condition is likely due to preferential hydrogen leakage.

The results of two stage purification indicated that the reduced overall flux observed during the recovery optimization testing was due primarily to membrane 4 performance. Flux measurements for membrane 4 have been lower than membranes 1 and 3 in all of our mixed gas testing. However, results of this last round of testing indicate that the Module 4 flux is 1/3 – ½ of what it was during shakedown testing. Flux through membranes 1 and 3 (Stage 1) did not appear to be degraded at all throughout the testing.

## 6 Conclusion and Discussion

The research done in this project showed advancements in many technical areas in support of large scale hydrogen production. Hydrogen rich synthesis gas was produced from waste material on a commercial scale. This is significant as municipal solid waste was heretofore not even considered as a potential large scale source of hydrogen. Furthermore, the Plasma Converter System has the potential for application not only to waste materials, but also to abundant biomass feedstocks that are not amenable to gasification by other methods for various reasons. The results of this testing also showed that the gas produced in a Plasma Converter System from municipal solid waste was very clean with 46% – 55 % hydrogen content before water gas shift. The gas produced was

suitable for many applications including subsequent purification through carbon molecular sieve membranes.

The membrane data obtained during this testing was also very significant. The membranes used were actual commercial scale membrane bundles (referred to as Modules) in this testing. Also, actual gasification gas was used from a non-fossil source as the feedstock for these membranes rather that clean natural gas. No sweep gases or other process aides were used that would improve performance statistics while decreasing the practical use of the gas. Even under these conditions, the StarCell system demonstrated gas purification from a 50% concentration to 96% purity and showed hydrogen recovery rates in excess of 86%.

Now that the performance baseline has been set for both the Plasma Converter System and the StarCell Hydrogen purification system, next step improvements can be made to both technologies. A significant area for improvement on the StarCell system is to increase the temperature capabilities to be more representative of high temperature applications. Higher separation temperatures will significantly improve membrane performance because flux is a logarithmic function of temperature. Higher temperature is also known to increase poison resistance of the membranes. Other StarCell research may include different types of membranes, counter current gas flows, or the incorporation of water gas shift directly into the membrane module. The Plasma Converter System used in this testing was designed for destruction of hazardous waste materials rather than low cost synthesis gas generation. Changes to the PCS relative to hydrogen production should focus on 3 areas; reducing even the trace quantities of sulfur species that are known to poison various catalysts used in water gas shift systems, reducing the amount nitrogen in the gas produced, and improving the energy efficiency of the torch system used to produce the Plasma.

# Appendix A

# Plasma Converter Description

STARTECH ENVIRONMENTAL CORP.

# Model PCS 5

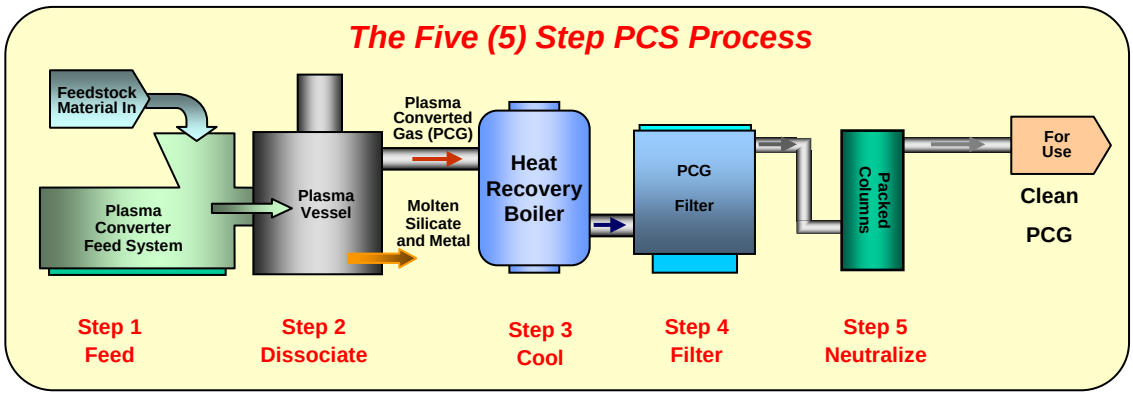
## Plasma Converter System (PCS)

**Plasma Converter System**


The PCS is a state-of-the-art process for the irreversible destruction of waste materials and the production of valuable products. It utilizes an electric arc to produce a very high temperature (up to 15,000ºC) ionized gas – the Plasma Plume. The aggressive plasma, and the high temperatures it generates in the Plasma Vessel, dissociates the waste materials into their elemental components. These elements are converted into either of two commercial products: a synthesis/fuel gas or an obsidian-like glassy stone.

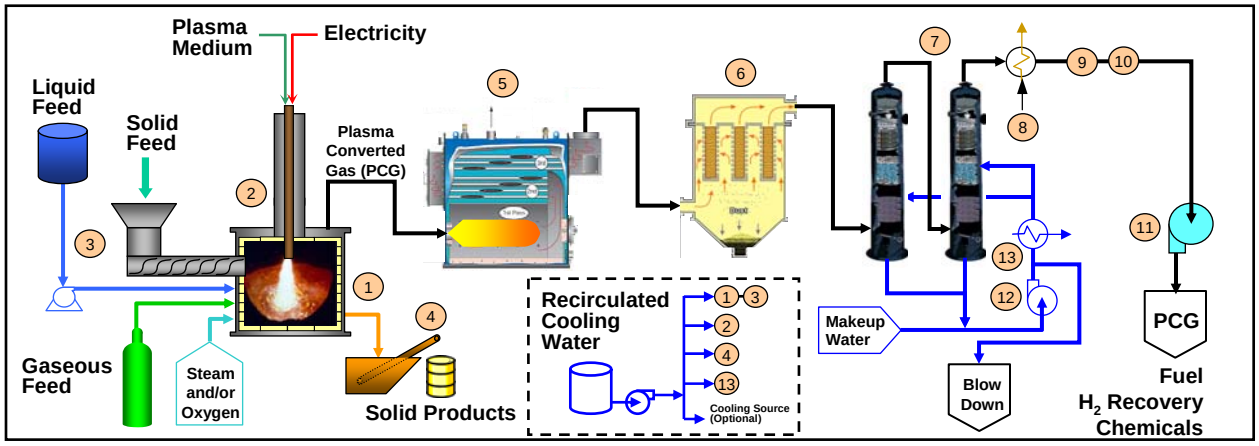
### PCS Benefits

- Greatly Reduces Costs and Risks Associated With Waste Generation
- Can Process Waste Materials in any Form, Simultaneously
- Safer Than Environmental Standards
- Recycles Wastes Into Valuable Commodity Products
- Systems are Sized to Convert Thousands of Pounds Per Day or Hundreds of Tons Per Day
- Stationary and Mobile Systems Available
- Safe and Irreversible Destruction of Even the Most Deadly Wastes
- Solid and Gas Commodity Products Produced During Conversion



STARTECH ENVIRONMENTAL CORP.

# Model PCS 5




1. **PLASMA CONVERTER:** Feed Material in all forms can be simultaneously dissociated into its elements in this insulated, high temperature, refractory lined S.S. vessel operating at slight vacuum. There are sealed openings in the vessel for the plasma torch, inspection ports, feedstock introduction and product (PCG & Melt) removal.
2. **PLASMA TORCH:** A water-cooled, D.C. powered dual electrode device which provides the energy required to ionize the plasma medium (e.g. Air, argon, etc.). The high operating temperature, up to 15,000ºC, enables the molecular dissociation to occur. The torch is mounted on the roof of the Plasma Converter and uses an operator controlled nutation system to optimize feedstock destruction.
3. **FEED SYSTEM:** Utilizes ram or auger mechanisms for solids, pump or steam eductor for liquids and pressure regulator valves for gaseous feeds from storage vessels. Oxygenated steam feed to the Converter enables stoichiometric control of the PCG quality based on feed composition.
4. **MELT EXTRACTION SYSTEM:** Utilizes dry cooling or a water quench of molten product to form particles which are conveyed to a collection drum.
5. **PCG COOLER/HRSG:** The primary PCG/Heat Recovery Steam Generator cools the PCG from 1,300ºC to 200ºC while generating steam for reuse. Powdered additives can be fed at this stage to prevent the formation of even trace levels of dioxins if required.
6. **PARTICLE FILTER:** A pulse-jet cartridge dust collector, capable of "blowing back" collected solids for recycling to the Plasma Converter. Filter aids may be added upstream of the Particle Filter to assure sub-micron filtration and/or perform dry acid gas scrubbing.
7. **PACKED COLUMN:** A two stage system rapidly quenches PCG from 200°C to 30°C. Acid gases are removed in these units. Sodium hydroxide or similar basic reagent is added to neutralize any acid gases that are scrubbed out of the PCG.
8. **PCG REHEATER:** PCG is heated above dew point using process heat or electricity.
9. **GAC FILTER:** Optional Granulated Activated Carbon filter (not shown).
10. **HEPA FILTER:** Optional High Efficiency Particle Abatement filter (not shown).
11. **ID FAN:** Maintains slight vacuum in the Plasma Converter**.**
12. **WATER RECIRCULATION PUMP:** Recirculates Gas Polisher water. A low flow of blow down water from the packed columns is sent to drain.
13. **HEAT EXCHANGER:** Removes heat from Gas Polisher water to recirculated cooling water system.

- Equipment Footprint Approximately 2000-2500 sf and 20 ft Minimum Ceiling Height Process Area

## CONTACT DATA


Marketing Department
15 Old Danbury Road, Suite 203
Wilton, Connecticut 06897
Phone: (203) 762-2499
Fax: (203) 761-0839
http://www.startech.net

# Appendix B

# Media and Process Technology membrane Information

# M&P CERAMIC MEMBRANES

Low cost high performance ceramic membranes have been developed at Media and Process Technology Inc. (M&P) for applications in crossflow micro- and ultra-filtration. Our innovative membrane technology delivers the performance advantages of ceramic materials at a cost comparable to polymeric membranes. "Expensive" capital and "niche" applications associated with traditional ceramic membranes are no longer barriers to prevent you from exploring M&P ceramic membranes in your applications. This brochure acquaints you with the general characteristics of this technological breakthrough offered by M&P.

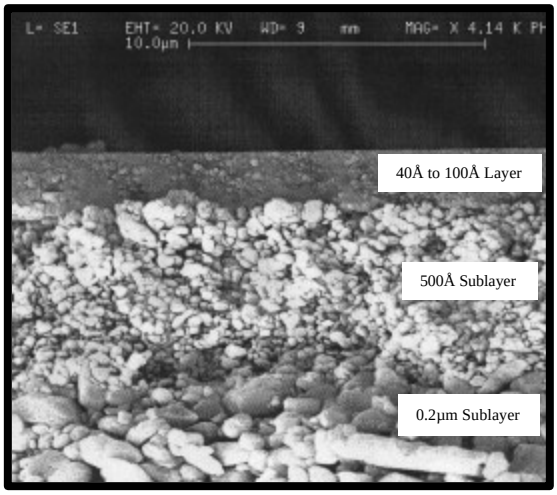



Figure 1. M&P Composite Ceramic Membrane

***Ceramic Membrane Performance…***

High performance no longer equals high cost with M&P ceramic membranes. The high quality and well-defined pore size distribution of M&P ceramic membranes yield fluxes and permeate quality which is superior to comparable polymeric membranes, but at a comparable cost.

***Ceramic Membrane Resistance…***

Because the membranes are constructed from ceramic materials, they offer exceptional tolerances in the most demanding of operating environments.

- *Temperatures > 400°C*
- *Burst pressure > 500 psi*
- *Steam sterilizable to ≥ 125°C*
- *pH resistant*
- *Excellent radiation resistance*
- *Unaffected by solvents, oxidants, etc.*
- *Rugged, reliable, long life > 5 years*

***Ceramic Membrane Construction…***

Sintered ceramic composite construction (Figure 1) yields a high strength membrane with a variety of pore sizes (Figure 2) to choose from to meet your application needs.

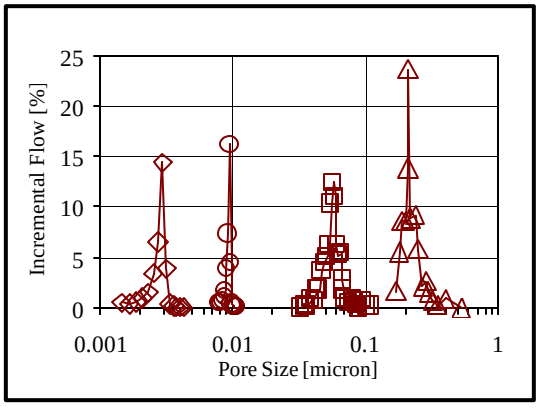



Figure 2. Pore Size Distributions of Various M&P Ceramic Membranes

**Table 1. Characteristics of M&P's Ceramic Ultrafilters and Microfilters**

| Characteristic | Ultrafilters | Microfilters |
|---|---|---|
| Active layer: | γ- or α-alumina | α-alumina |
| Pore Size: | 40Å to 0.2µm | 0.5 to 3µm |

MEDIA & PROCESS TECHNOLOGY INC.
1155 William Pitt Way
Pittsburgh, PA 15238
(412) 826-3721 (412) 826-3720

***Ceramic Membrane Specifications…***Ceramic membrane elements are available as monoliths or hollow fiber/tubular bundles (Figure 3). Membranes range in size from 30 to 40" in length and from 1.25 to 4" in diameter. Depending upon the configuration, membrane area varies from 0.2 to 2.0 $m^2$ per element. Elements with surface areas in excess of 2 $m^2$ can be readily fabricated using the hollow fiber/tubular parts bundled into packages >4" in diameter. Membrane element(s) are housed in modules (Figure 4) constructed of carbon and stainless steel and CPVC. Other module materials are readily available to meet your application needs.

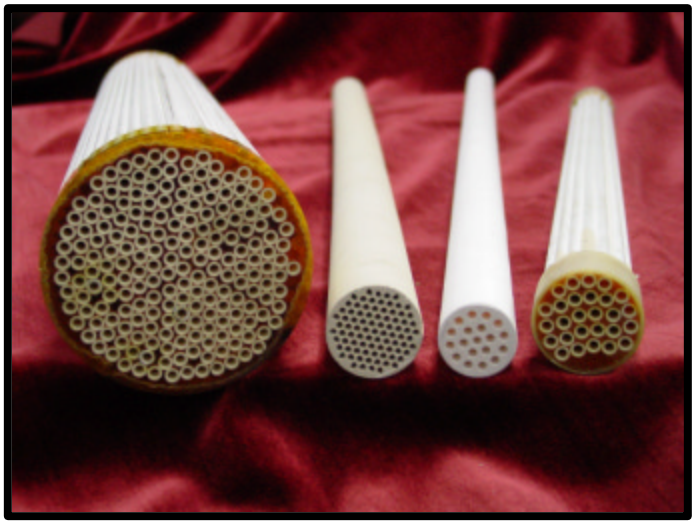


Figure 3. M&P Hollow Fiber/Tubular and Monolithic Ceramic Membrane Products

***Ceramic Membrane Experience…***
M&P offers not only an advanced membrane technology, but also years of experience in membrane-based applications. From laboratory treatability testing to full-scale process realization, M&P can deliver a ceramic membrane to meet your needs in the most demanding environment.

***Ceramic Membrane Applications…***
Selected applications having been demonstrated include:

- Potable water production
- RO pretreatment
- Municipal wastewater disinfection
- Treatment of industrial wastewaters: textiles, laundries, metal working, primary metals, parts washing
- Aqueous alkaline cleaner recovery
- Used solvent reclamation
- Used oil recovery

M&P ceramic membranes can reduce your operating costs significantly while delivering high quality product for use, recycle, or disposal.

***Ceramic Membrane Advantages…***
M&P's high performance ceramic membranes are comparable in price to polymeric membranes yet will last significantly longer. Hence, your capital and operating costs will be dramatically reduced in comparison to other membrane technologies.

Figure 4. M&P Ceramic Membrane Modules

MEDIA & PROCESS TECHNOLOGY INC.
1155 William Pitt Way
Pittsburgh, PA 15238
(412) 826-3721 (412) 826-3720

# Appendix C

# Coal Gas Detailed Data Summary

## Summary of Coal Gas Contaminant Analysis

| Test Parameter | Results description |
|---|---|
| Siloxanes, HAP | Very Low. Almost all below the detection limit. A couple detected but near detection limit. CS2~77 ug/dscm, Flyer hit for Acetone. |
| Mercaptans | None Detected |
| Heavy Metals (Ag, As, Ba, Cd, Cr, Hg, Pb, Se) | All metals were either in the non-detect or ug / dscm range (very low). Metals of particular concern with coal: Hg 0.8 ug/dcsm, Pb 3.9 ug/dscm, Cr 2.0 ug/dscm, Cd 0.2 ug/dscm, Ba None detected. |
| SO2, SO3 | None detected |
| CO, CO2, CH4, N2, O2 | See section 4.1.3.3 |
| H2 | See section 4.1.3.3 |
| Permanent Gases | Almost no non-methane hydrocarbons. Very good for membrane performance. 470 ppm CH4, ~5 ppm of Acetylene and Ethene, Non detect on all others. |
| Dioxin / Furan | Very Low, 0.005 ng/dscm CDD TEF, 0.002 ng/dscm CDF TEF |
| SVOC | Very Low, Almost all non-detects. |
| Hydrogen Cyanide | None Detected |
| Hydrogen Sulfide | None Detected |
| Oxides of Nitrogen | Avg. 190 ppm |
| O2 /CO2 | See section 4.1.3.3 |
| ISO Kinetic Particulate Sampling | Extremely Low; 0.3 mg/dscm. Very Good for membrane performance |
| HCL / CL2 | None detected |
| Ammonia | None detected |

# Appendix D

# MSW Gas Detailed Data Summary

## Summary of MSW Gas Contaminant Analysis

| Test Parameter | Results description |
|---|---|
| Siloxanes, HAP | Very Low to none detected on all. CS2 7.9 mg/dscm. |
| Mercaptans | None Detected for Mercaptan and all sulfur compounds except COS 22 mg/dscm and CS2 0.004 mg/dscm |
| Heavy Metals (Ag, As, Ba, Cd, Cr, Hg, Pb, Se) | All metals were either in the non-detect or ug / dscm range (very low). Metals of particular concern with coal: Hg 0.2 ug/dcsm, Pb 1.2 ug/dscm, Cr 3.2 ug/dscm, Cd 0.2 ug/dscm, Ba None detected. |
| SO2, SO3 | None Detected |
| CO, CO2, CH4, N2, O2 | See section 4.2.3.2 |
| H2 | See section 4.2.3.2 |
| Permanent Gases | No non-methane hydrocarbons detected. Very good for membrane performance. ~1% CH4. |
| Dioxin / Furan | Very Low, 0.0035 ng/dscm CDD TEF, 0.0045 ng/dscm CDF TEF |
| SVOC | Very low. Non Detect on all except the following: 2 methylphenol 0.004 mg/dscm, Benzoic Acid 0.027 mg/dscm, Benzyl Alcohol 0.159 mg/dscm, Bis(2ethylhexyl)phthalate 0.007 mg/dscm, Naphthalene 0.006 mg/dscm |
| Hydrogen Cyanide | 5 mg/dscm |
| Hydrogen Sulfide | None Detected |
| Oxides of Nitrogen | 221 ppm dry |
| O2 /CO2 | See section 4.2.3.2 |
| ISO Kinetic Particulate Sampling | Extremely Low; 0.4 mg/dscm. Very Good for membrane performance |
| HCL / CL2 | None Detected |
| Ammonia | None Detected |

# Appendix E

# StarCell Data Sheets

| Run Date | Membranes Used | | Gas Feed Composition |
|---|---|---|---|
| | Stage 1 | Stage 2 | |
| 9/8/2005 | 1 | | 50% He / 50% N2 |
| | | 3 | 1st stage permeate |
| 9/9/2005 | 1 | | 50% He / 50% N2 |
| 9/12/2005 | 1 | | 50% He / 50% N2 |
| 9/13/2005 | 1 | | 50% He / 50% N2 |
| 9/14/2005 | 1 | | 50% He / 50% N2 |
| | | 3 | 1st stage permeate |
| 9/21/2005 | 1 & 3 | | 50% H2 / 50% CO |
| 9/22/2005 | 1 & 3 | | 50% H2 / 50% CO |
| | | 4 | 100% N2 |
| 9/23/2005 | 1 & 3 | | 100% H2, 100% N2 |
| | | 4 | 100% H2, 100% N2 |
| 10/4/2005 | 1 | | 100% H2, 100% N2 |
| 10/5/2005 | | 3 | 100% H2, 100% N2 |
| 11/30/2005 | 1 & 3 | | PCG (Surrogate MSW feed) |
| 12/1/2005 | 1 & 3 | | PCG (Surrogate MSW feed) |
| 1/11/2006 | 1, 3, & 4 | | PCG (Surrogate MSW feed) |
| 1/12/2006 * | 1, 3, & 4 | | PCG (Surrogate MSW feed) |
| 1/12/2006 | | 4.0 | 1st stage permeate |
| | | | |
| | | | |
| NOTES: | | | |
| Membranes 1 to 3 are MP&T generation 2 membranes | | | |
| Membrane 4 are MP&T generation 3 membrane | | | |
| * - Membrane 4 was used to separate PCG until 100PSIG was obtained in stage 2 feed | | | |
| tank (TK703). Membrane 4 was then switched for stage 2 processing and purged using | | | |
| Stage 1 permeate gas. | | | |
| | | | |
| | | | |
| | | | |
| | | | |

STARTECH ENVIRONMENTAL CORP

Stage 1 - 09-08-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | | |
| 8:30 | Start gas analyzer | | | | | | | | | | |
| 10:00 | Start 50/50 He/CO span gas | | | | | | | | | | |
| 10:09 | Confirm 50% reading of gas analyzer | | | | | | | | | | |
| 10:15 | Start He/N2 flow thru membranes 1 & 2 | | | | | | | | | | |
| 10:32 | Confirm membrane #2 leaks. Run membrane 1 only | | | | | | | | | | |
| 11:09 | 101 | 109.1 | 101.0 | 114.0 | 3.2 | 1.3 | 1.3 | 37 | 62 | 49 | 82 |
| 11:28 | 99.8 | 107.8 | 100.1 | 126.4 | 3.6 | 4.4 | 1.24 | 38 | 62 | 50 | 82 |
| 12:05 | 99.9 | 104 | 100.6 | 140.4 | 3.2 | 11.3 | 1.12 | 39 | 62 | 51 | 82 |
| 12:25 | 95.2 | 103.4 | 95.9 | 142.6 | 3.5 | 14 | 1.03 | 40 | 62 | 53 | 82 |
| 12:55 | 92.1 | 102 | 92.2 | 143.3 | 3.3 | 19.8 | 0.88 | 40 | 62 | 53 | 82 |
| 1:30 | 60 | 103 | 59.2 | 139.7 | 2.0 | 23.4 | 0.41 | 42 | 60 | 55 | 79 |
| 1:35 | Change feed gas bottle, reset pressure to PSIG | | | | | | | | | | |
| 1:55 | 99.1 | 103.6 | 99.3 | 144.9 | 3.7 | 26.7 | 0.89 | 41 | 61 | 54 | 80 |
| 2:20 | 97.1 | 103.2 | 97.4 | 147.2 | 3.6 | 30 | 0.81 | 41 | 61 | 54 | 80 |
| 2:45 | 99.7 | 102.7 | 99.9 | 155.1 | 3.3 | 33.3 | 0.74 | 43 | 61 | 57 | 80 |
| 3:10 | 99 | 104.1 | 99.3 | 151.6 | 3.3 | 34.5 | 0.78 | 43 | 61 | 57 | 80 |
| 3:25 | 96.8 | 105 | 97.1 | 151.7 | 3.7 | 36.3 | 0.72 | 43 | 61 | 57 | 80 |
| 3:56 | 98.9 | 105.7 | 99.2 | 150.4 | 3.4 | 37.7 | 0.73 | 43 | 61 | 57 | 80 |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

Initially used membrane housings 1 & 2, performed tests on membrane 1 only
Used 100 % N2 and 50:50 H2/CO for zero and span gas (respectively) prior to testing
%H correction factor: 100/76= 1.3158 due to improper readings on analyzer
Used 50:50 He/N2 for gas feed testing

STARTECH ENVIRONMENTAL CORP.

Stage 1 - 09-09-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | | |
| 8:30 | Start Gas feed to Stage 1 | | | | | | | | | | |
| 8:35 | 95.8 | 44.3 | 95.9 | 41.3 | 3 | 39.9 | 0.64 | 41 | 59 | 54 | 78 |
| 8:50 | 95.7 | 41.9 | 95.8 | 48.6 | 3 | 40.3 | 0.61 | 42 | 59 | 55 | 78 |
| 9:00 | Readjust press. Inlet and reject flowrate to 100 PSIG and 3.0 LPM, respectively (ongoing) | | | | | | | | | | |
| 9:35 | 101.8 | 37.5 | 102 | 61.2 | 3 | 45.3 | 0.61 | 42 | 59 | 55 | 78 |
| 10:53 | 103.1 | 37.5 | 101.9 | 61.6 | 3.1 | 47.4 | 0.58 | 42 | 59 | 55 | 78 |
| 11:50 | 101.5 | 36.8 | 102.4 | 63 | 2.8 | 53 | 0.54 | 43 | 58 | 57 | 76 |
| 12:30 | 102.8 | 37.2 | 103 | 61.7 | 2.9 | 53.3 | 0.54 | 43 | 58 | 57 | 76 |
| 1:20 | 101.2 | 37.2 | 101.4 | 61 | 2.9 | 48.4 | 0.59 | 43 | 59 | 57 | 78 |
| 1:55 | 99.8 | 37.2 | 100 | 61.1 | 2.9 | 45.7 | 0.61 | 44 | 60 | 58 | 79 |
| 2:05 | Baseline recalibration - 100% N2 - inlet press. @100 PSIG | | | | | | | | | | |
| 2:12 | 99.1 | 42.1 | 99.4 | 58.5 | 3 | 0 | 0.5 | 0 | 0 | 0 | 0 |
| 2:37 | 100 | 42.1 | 100.2 | 60.6 | 3.5 | 0 | 0.53 | 0 | 0 | 0 | 0 |
| 2:47 | Baseline recalibration - 100% H2 - inlet press. @100 PSIG | | | | | | | | | | |
| 2:50 | 95.7 | 39.2 | 96.1 | 59.4 | 3.3 | 6.6 | 5.1 | 76 | 76 | 100 | 100 |
| 3:05 | 97 | 36.3 | 97.2 | 60 | 3.1 | 22.3 | 4.46 | 76 | 76 | 100 | 100 |
| 3:20 | Recalibrate using 100% H2 for span gas: old reading of 76% adjusted to 100% | | | | | | | | | | |
| 3:47 | 92.4 | 39.8 | 92.8 | 51.5 | 3.7 | 5.8 | 1.12 | 53 | 87 | | |
| 3:58 | 97.8 | 38.8 | 98 | 53.2 | 3.3 | 6.1 | 1.18 | 52 | 87 | | |
| 4:09 | 100.8 | 37.9 | 101.1 | 54.7 | 3 | 7.4 | 1.2 | 52 | 88 | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

Used membrane housing 1
Used 100 % N2 and 50:50 H2/CO for zero and span gas (respectively) prior to testing
%H correction factor: 100/76= 1.3158 due to improper readings on analyzer
Used 50:50 He/N2 for gas feed testing

STARTECH ENVIRONMENTAL CORP.

Stage 2 - 09-09-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor. Reject | Cor. Perm. |
| | PE707 | TE705 | PE708 | TE706 | FE703 | PE709 | FE704 | | | | |
| 12:32 | Start gas feed to Stage 2 | | | | | | | | | | |
| 12:36 | 52.3 | 38.1 | 52.1 | 42.9 | 0.48 | 5.3 | 0.34 | 55 | 66 | 72 | 87 |
| 12:48 | Closed permeate outlet valve, determine %H in feed to be 59% @ 0.71 LPM | | | | | | | | | | |
| 1:25 | 48.1 | 36.7 | 47 | 61.1 | 0.49 | 5.7 | 0.37 | 53 | 66 | 70 | 87 |
| 1:55 | 45.9 | 36.4 | 45.8 | 47.5 | 0.23 | 2.9 | 0.35 | 54 | 67 | 71 | 88 |

Used membrane housing 3
Used 100 % N2 and 50:50 H2/CO for zero and span gas (respectively) prior to testing
%H correction factor: 100/76= 1.3158 due to improper readings on analyzer
Used 1st stage permeate for gas feed testing

STARTECH ENVIRONMENTAL CORP

Stage 1 - 09-12-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | | |
| 12:55 | Start gas feed to stage 1 | | | | | | | | | | |
| 12:58 | 97.4 | 43.1 | 97.5 | 40.1 | 3.5 | 8.6 | 1.14 | 52 | 84 | | |
| 1:08 | 98.5 | 41.4 | 98.8 | 44.7 | 3.2 | 9.8 | 1.12 | 52 | 84 | | |
| 1:27 | 96.2 | 38.2 | 96.5 | 53 | 3.6 | 13.4 | 1.04 | 54 | 84 | | |
| 2:04 | 98.9 | 36.1 | 99.2 | 59.3 | 3.3 | 17.4 | 1.02 | 55 | 85 | | |
| 2:28 | 96.2 | 35.6 | 91.4 | 61.7 | 3.4 | 21.4 | 0.95 | 56 | 85 | | |
| 2:33 | Calibrate span with 100% H2 | | | | | | | | | | |
| 2:35 | Calibrate zero with 100% N2 | | | | | | | | | | |
| 2:38 | Test with 50/50 H2/CO = 68% | | | | | | | | | | |
| 3:00 | Calibrate zero and span with 100%N2 and 100%H2, respectively | | | | | | | | | | |
| 3:34 | 96 | 35.9 | 96.4 | 62.1 | 3.7 | 31.1 | 0.78 | 56 | 83 | | |
| 3:50 | %H2 reading of feed gas: 50/50 He/N2 = 43% Reject = 61.5 PSIG, Permeate = 46.7 PSIG | | | | | | | | | | |
| 3:55 | Set zero using 50% H2/50% CO at 50%H2 | | | | | | | | | | |
| 4:30 | Shutdown. TK702= 37.0 PSIG | | | | | | | | | | |

Used membrane housing 1

Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing

Used 50:50 He/N2 for gas feed testing

STARTECH ENVIRONMENTAL CORP

Stage 1 - 09-13-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | | |
| 3:58 | 46.1 | 43.5 | 96.3 | 40.7 | 3.3 | 36.2 | 0.7 | 40 | 69 | | |
| 4:12 | 99.3 | 40.7 | 99.9 | 48.5 | 3.2 | 37.5 | 0.71 | 41 | 73 | | |
| 4:24 | 98.6 | 38.9 | 98.4 | 53.4 | 3.5 | 38.3 | 0.66 | 40 | 73 | | |
| 4:28 | % H2 in feed gas 50%He/50%N2 = 47% Reject = 62.6 PSIG, Permeate = 49.7 PSIG | | | | | | | | | | |

Used membrane housing 1
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing

Used 50:50 He/N2 for gas feed testing

STARTECH ENVIRONMENTAL CORP

Stage 1 - 09-14-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | | |
| 7:40 | Start analyzers | | | | | | | | | | |
| 9:20 | Calibrate zero and span witrh 100%N2 and 100%H2, respectively | | | | | | | | | | |
| 9:35 | %H2 reading of feed gas: 50/50 He/N2 = 43% Reject = 61.5 PSIG, Permeate = 46.7 PSIG | | | | | | | | | | |
| 9:29 | 101.1 | 42.6 | 101.3 | 41.3 | 3 | 37.8 | 0.75 | 39 | 61 | 46.8 | 73.2 |
| 9:45 | 101.5 | 41 | 100.7 | 47.1 | 2.4 | 39 | 0.67 | 37 | 67 | 44.4 | 80.4 |
| 10:11 | 99 | 38.8 | 99.3 | 52.3 | 2.4 | 41.2 | 0.62 | 39 | 66 | 46.8 | 79.2 |
| 10:35 | 98.6 | 38.1 | 98.3 | 55 | 2.7 | 43.3 | 0.58 | 39 | 66 | 46.8 | 79.2 |
| 11:20 | 99.1 | 37.6 | 99 | 56.9 | 2.7 | 46.5 | 0.54 | 40 | 66 | 48 | 79.2 |
| 12:02 | 98.1 | 37.3 | 99 | 57.5 | 2.5 | 49.8 | 0.52 | 41 | 65 | 49.2 | 78 |
| 12:50 | 98.6 | 37.8 | 98.8 | 56.6 | 2.5 | 48.1 | 0.54 | 40 | 66 | 48 | 79.2 |
| 1:25 | 97.7 | 37.7 | 98.4 | 56.2 | 2.6 | 46.8 | 0.57 | 40 | 67 | 48 | 80.4 |
| 1:55 | 98.9 | 37.8 | 99.2 | 56.1 | 2.5 | 46.3 | 0.57 | 40 | 67 | 48 | 80.4 |
| 2:15 | 97.7 | 37.6 | 98.1 | 56.3 | 2.5 | 45.6 | 0.57 | 40 | 67 | 48 | 80.4 |
| 2:20 | Lower flowrate of reject | | | | | | | | | | |
| 2:53 | 100.6 | 38.2 | 100.8 | 55.5 | 1.3 | 45.4 | 0.57 | 38 | 66 | 45.6 | 79.2 |
| 3:20 | 99.1 | 40.4 | 100 | 51.1 | 1.4 | 44 | 0.59 | 37 | 66 | 44.4 | 79.2 |
| 3:50 | 98.7 | 41.5 | 98.9 | 49.8 | 1.3 | 44.3 | 0.56 | 37 | 66 | 44.4 | 79.2 |
| 4:16 | 97.8 | 41.8 | 98.4 | 49.3 | 1.3 | 44.1 | 0.57 | 36 | 66 | 43.2 | 79.2 |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

Used membrane housing 1
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
%H correction factor: 1.2
Used 50:50 He/N2 for gas feed testing

STARTECH ENVIRONMENTAL CORP

Stage 2 - 09-14-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor. Reject | Cor. Perm. |
| | PE707 | TE705 | PE708 | TE706 | FE703 | PE709 | FE704 | | | | |
| 12:05 | Start 2 stage feed | | | | | | | | | | |
| 12:07 | 49.1 | 37 | 49 | 42.7 | 0.3 | 10.9 | 0.32 | 77 | 79 | 92 | 95 |
| 12:50 | 36.3 | 48.2 | 48.1 | 45 | 0.37 | 6.7 | 0.15 | 51 | 80 | 61 | 96 |
| 1:25 | 47 | 35.8 | 46.8 | 45 | 0.22 | 0.4 | 0.32 | 54 | 81 | 65 | 97 |
| 1:55 | 46.4 | 35.7 | 46.3 | 45.4 | 0.22 | 0.4 | 0.31 | 49 | 80 | 59 | 96 |
| 2:15 | 45.7 | 35.5 | 45.6 | 45.2 | 0.22 | 0.4 | 0.3 | 50 | 81 | 60 | 97 |
| 2:53 | 45.3 | 35.5 | 45.2 | 45.5 | 0.22 | 0.4 | 0.31 | 50 | 80 | 60 | 96 |
| 3:20 | 44.1 | 35.5 | 44 | 45 | 0.21 | 0.4 | 0.29 | 50 | 81 | 60 | 97 |
| 3:50 | 44.4 | 35.7 | 44.3 | 45.3 | 0.17 | 0.4 | 0.31 | 45 | 78 | 54 | 94 |
| 4:16 | 44.2 | 35.8 | 44.1 | 44.6 | 0.17 | 0.4 | 0.26 | 45 | 79 | 54 | 95 |

Used membrane housing 3
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
%H correction factor: 1.2
Used 1st stage permeate for gas feed testing

STARTECH ENVIRONMENTAL CORP

Stage 1 - 09-21-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 * | FE702 | | | | |
| 2:10 | Start naalyzers | | | | | | | | | | |
| 2:24 | Initial calibration of zero & span gas w/ 100% N2 & 100% H2 | | | | | | | | | | |
| 2:30 | Start feed | | | | | | | | | | |
| 2:34 | 97.1 | 46 | 97.1 | 44.5 | 2.5 | 3.5 | 2.7 | 20 | 80 | | |
| 2:50 | 96.2 | 41.9 | 96.4 | 50.5 | 2.2 | 5.7 | 2.55 | 24 | 82 | | |
| 3:18 | 97.4 | 37.8 | 97.6 | 57.1 | 2.4 | 9.6 | 2.48 | 25 | 81 | | |
| 3:36 | 97.5 | 36.9 | 97.7 | 58.7 | 2.7 | 6.9 | 2.65 | 22 | 80 | | |
| 4:00 | 97.3 | 36.2 | 97.5 | 60 | 2.7 | 6.9 | 2.66 | 22 | 80 | | |
| 4:10 | calibrate zero & span gas with 100% N2 & 100% H2 | | | | | | | | | | |
| 4:15 | Measured H2 in feed gas: 50% H2/50% CO = 53% H2 | | | | | Reject = 19.6 PSIG | | Permeate = 14.8 PSIG | | | |
| 4:58 | 96.7 | 36.3 | 96.9 | 59.5 | 3 | 8.1 | 2.67 | 24 | 80 | | |

Used membrane housing 1 & 3
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
Used 50:50 H2/CO for gas feed testing
* pressure varies due to AC702 (compressor regulates TK702 pressure between 10 & 5 PSIG)

STARTECH ENVIRONMENTAL CORP

Stage 1 - 09-22-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 * | FE702 | | | | |
| 9:11 | Turn on system | | | | | | | | | | |
| 9:29 | 101.8 | 40.7 | 102.0 | 48.0 | 3.1 | 8.0 | 2.82 | 22 | 76 | | |
| 10:07 | 101.9 | 36.2 | 102.1 | 58.4 | 2.6 | 9.3 | 2.67 | 24 | 79 | | |
| 10:33 | 102.0 | 35.5 | 102.3 | 60.6 | 2.5 | 6.1 | 2.7 | 23 | 80 | | |
| 10:57 ^ | 102.3 | 35.5 | 102.5 | 61.4 | 2.7 | 8.8 | 2.72 | 24 | 80 | | |
| 11:11 | 102.5 | 25.6 | 102.8 | 61.9 | 2.7 | 7.3 | 2.78 | 23 | 80.5 | | |
| 11:53 | 102.8 | 35.9 | 103.1 | 62.5 | 2.8 | 7.0 | 2.81 | 23 | 80 | | |
| 12:15 | 103.1 | 36.1 | 103.3 | 62.7 | 2.8 | 7.4 | 2.81 | 23 | 80.5 | | |
| 12:45 | | | | | | | | | | | |
| 1:07 | 103.6 | 36.1 | 103.8 | 63.0 | 2.7 | 6.1 | 2.88 | 23 | 81 | | |
| 2:08 | 101.3 | 35.9 | 101.6 | 63.0 | 2.9 | 5.6 | 2.83 | 23 | 81.5 | | |
| 2:35 | 102.1 | 35.8 | 102.4 | 63.0 | 2.9 | 7.6 | 2.79 | 23.5 | 81.5 | | |
| 3:13 | 102.4 | 35.7 | 102.7 | 63.0 | 2.9 | 5.4 | 2.85 | 23 | 82 | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

Used membrane housing 1 & 3
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
Used 50:50 H2/CO for gas feed testing
* pressure varies due to AC702 (compressor regulates TK702 pressure between 10 & 5 PSIG)
^ prior to this time, the TCD was reading low, starting at 10% below and then slowly autocorrecting

STARTECH ENVIRONMENTAL CORP

Stage 2 - 9-22-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor. Reject | Cor. Perm. |
| | PE707 | TE705 | PE708 | TE706 | FE703 | PE709 | FE704 | | | | |
| 10:23 | 77.8 | 37.6 | 77.7 | 49.9 | 0.71 | | | | | | |
| | Start feeding 100% N2 | | | | | | | | | | |
| 10:27 | 77.5 | 37.4 | 77.4 | 51.1 | 0.7 | 1.0 | 0.57 | 47 | 90 | | |
| 10:54 | 76.5 | 36.5 | 76.3 | 55.8 | 1.3 | 1.3 | 0.72 | 49 | 92 | | |
| 11:11 | 76.4 | 35.6 | 76.3 | 58.2 | 1.3 | 1.3 | 0.75 | 51 | 93 | | |
| 11:54 | 76.8 | 34.8 | 76.6 | 58.1 | 0.9 | 1.2 | 0.75 | 50 | 92 | | |
| 12:16 | 76.8 | 34.4 | 76.6 | 58.5 | 0.9 | 1.2 | 0.78 | 52 | 93 | | |
| 1:07 | 100.7 | 34.2 | 100.4 | 61.0 | 1.0 | 1.2 | 1.13 | 51 | 94 | | |
| 2:08 | 100.5 | 34.1 | 100.2 | 61.5 | 1.2 | 1.3 | 1.28 | 56 | 95 | | |
| 2:36 | 100.3 | 33.9 | 100.1 | 61.2 | 1.0 | 1.2 | 1.21 | 56 | 96 | | |
| 3:16 | 100.4 | 33.9 | 100.1 | 60.3 | 1.0 | 1.3 | 1.25 | 57 | 96.5 | | |

Used membrane housing 4
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
During testing, inlet pressure (PE707) was set at 75 & 100 PSIG
During testing, reject flow (FE703) was set to 0.75 & 1.00 LPM
Recorded pressures and flows with analyzer measuring zero gas
* - not enough line pressure to feed gas to analyzer

STARTECH ENVIRONMENTAL CORP

Stage 2 - 9-22-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | | |
| 9:05 | Start analyzers | | | | | | | | | | |
| 10:15 | calibrate zero and span | | | | | | | | | | |
| 11:07 | Start 100% H2 feed | | | | | | | | | | |
| 11:12 | 97.7 | 44.7 | 97.8 | 39.8 | 2.6 | 79.1 | 2.92 | 100 | 98 | | |
| 11.:20 | 96.7 | 37.7 | 97 | 42.3 | 2.5 | 70.6 | 3.14 | 100 | 100 | | |
| 11:31 | 99.2 | 35.5 | 99.2 | 48 | 2.6 | 71.6 | 3.26 | 100 | 100 | | |
| 11:44 | 99.3 | 45.5 | 99.3 | 51.8 | 2.6 | 71.5 | 3.28 | 100 | 100 | | |
| 11:46 | Start 100% N2 feed | | | | | | | | | | |
| 12:03 | 99 | 45.5 | 99.2 | 53.9 | 1.5 | 27.4 | 0.53 | 0 | 10 | | |
| 12:31 | 98.9 | 48.3 | 99.2 | 55.2 | 1.6 | 17.8 | 0.4 | 0 | 0 | | |
| 12:43 | 98.9 | 48.2 | 99.2 | 55.8 | 1.6 | 30.4 | 0.58 | 0 | 0 | | |
| 12:49 | 98.9 | 48.9 | 99.2 | 56.8 | 1.6 | 26.1 | 0.51 | 0 | 0 | | |

Used membrane housing 1 & 3
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
During testing, pressure (PE702) and flow (FE701) were set and monitored
Recorded pressures and flows with analyzer measuring zero gas

STARTECH ENVIRONMENTAL CORP.

Stage 2 - 9-23-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor. Reject | Cor. Perm. |
| | PE707 | TE705 | PE708 | TE706 | FE703 | PE709 | FE704 | | | | |
| 10:30 | Feed gas from TK703 = 65% H2 | | | | | | | | | | |
| 12:53 | Start feeding 100% N2 | | | | | | | | | | |
| 1:00 | 100.2 | 42.9 | 100 | 55.3 | 1.07 | 0.1 | 0.08 | 5 | * | | |
| 1:08 | 100.1 | 42.8 | 99.9 | 61.4 | 1.04 | 0.1 | 0.13 | 0 | * | | |
| 1:20 | 100.2 | 45 | 100 | 62.2 | 1.04 | 0.1 | 0.13 | 0 | * | | |
| 1:27 | 100.3 | 45.3 | 100 | 62.8 | 1.04 | 0.1 | 0.13 | 0 | * | | |
| 1:29 | Start feeding 100% H2 | | | | | | | | | | |
| 1:35 | 98.4 | 41.4 | 98.7 | 58.2 | 1.12 | 0.2 | 3.18 | 100 | 100 | | |
| 1:43 | 98.6 | 39.4 | 98.4 | 58 | 1.35 | 0.2 | 3.46 | 100 | 100 | | |
| 1:47 | 98.6 | 38.2 | 98.4 | 58.2 | 1.36 | 0.2 | 3.47 | 100 | 100 | | |
| 1:50 | 98.6 | 37.8 | 98.4 | 58.2 | 1.36 | 0.2 | 3.47 | 100 | 100 | | |

Used membrane housing 4
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
During testing, pressure (PE707) and flow (FE703) were set and monitored
Recorded pressures and flows with analyzer measuring zero gas
* - not enough line pressure to feed gas to analyzer

STARTECH ENVIRONMENTAL CORP

Stage 1 sheet1 -10-04-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | | |
| | | | MEMBRANE #1 | | | | | | | | |
| 7:40 | TURN ON ANALYZER | | | | | | | | | | |
| | | | | | | | | | | | |
| 10:10 | CAL. W/ SPAN & ZERO GAS | | | | | | | | | | |
| 11:20 | START 100% H2 FLOWRATE AT 0.8 LPM | | | | | | | | | | |
| 11:25 | 97.4 | 43.4 | 97.4 | 38.2 | 0.8 | 0.3 | 5.21 | 96 | 96 | | |
| 11:38 | 96.4 | 38.8 | 96.6 | 39.1 | 0.9 | 0.3 | 5.25 | 96 | 96 | | |
| 12:00 | 96.8 | 34.8 | 97 | 41 | 0.9 | 0.2 | 5.29 | 96 | 96 | | |
| 12:05 | RECAL. SPAN & 100% H2 96 to 100 | | | | | | | | | | |
| 12:10 | 98.7 | 35.8 | 98.8 | 42.3 | 1.0 | 0.2 | 5.36 | 100 | 100 | | |
| 12:12 | CHANGE 100% H2 FLOWRATE TO 1.6 LPM | | | | | | | | | | |
| 12:15 | 99.1 | 34.7 | 99.8 | 41.4 | 1.6 | 0.2 | 5.42 | 100 | 100 | | |
| 12:35 | 98.9 | 34.2 | 99.1 | 43.5 | 1.7 | 0.2 | 5.40 | 100 | 100 | | |
| 12:50 | 99.1 | 34.2 | 99.4 | 45.4 | 1.8 | 0.2 | 5.41 | 100 | 100 | | |
| 12:59 | 99.2 | 34.4 | 99.4 | 45.9 | 1.6 | 0.2 | 5.42 | 100 | 100 | | |
| 1:01 | CHANGE 100% H2 FLOWRATE TO 2.4 LPM | | | | | | | | | | |
| 1:03 | 99.8 | 34.5 | 100.1 | 47.1 | 2.4 | 0.2 | 5.44 | 100 | 100 | | |
| 1:13 | 99.7 | 34.8 | 99.9 | 48.9 | 2.5 | 0.2 | 5.44 | 100 | 100 | | |
| 1:32 | 99.9 | 35.5 | 100.1 | 52.3 | 2.6 | 0.2 | 5.46 | 100 | 100 | | |
| 1:47 | 100.1 | 35.8 | 100.4 | 53.1 | 2.4 | 0.2 | 5.47 | 100 | 100 | | |
| 1:50 | CHANGE TO 100% N2, SET FLOWRATE TO 0.8 LPM | | | | | | | | | | |
| 1:53 | 100.8 | 41.7 | 101.0 | 52.4 | 0.8 | 0.1 | 0.45 | 10 | No Pressure from Membrane | | |
| 2:06 | 100.7 | 42.7 | 100.9 | 51.2 | 0.8 | 0.1 | 0.48 | 0 | | | |
| 2:24 | 100.9 | 51.1 | 101.2 | 49.5 | 0.7 | 0.1 | 0.48 | | | | |
| 2:33 | 100.8 | 52.2 | 101.1 | 48.9 | 0.7 | 0.1 | 0.48 | | | | |
| 2:35 | CHANGE 100% N2 FLOWRATE TO 1.4 LPM | | | | | | | | | | |
| 2:40 | 100.8 | 51.3 | 101 | 49.2 | 1.3 | 0.1 | 48 | | | | |
| 3:03 | 100.8 | 51.6 | 101 | 49.7 | 1.3 | 0.1 | 0.49 | | | | |
| 3:18 | 100.7 | 51.7 | 101 | 49.9 | 1.3 | 0.1 | 0.48 | | | | |

Used membrane housing 1
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
Used 100 % N2 and 100% H2 for testing
Cabinet temperature 255 to 257°F
Readings were taken (excluding %H2) with zero gas being fed into analyzers

Stage 1 sheet2 10-04-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | | |
| 3:34 | 100.8 | 54.9 | 101.1 | 48.1 | 0.4 | 0.1 | 0.49 | | | | |
| 3:46 | 100.8 | 55.4 | 101.0 | 47.3 | 0.4 | 0.1 | 0.49 | | | | |
| 4:08 | 100.8 | 56 | 101.0 | 46.6 | 0.4 | 0.1 | 0.49 | | | | |

Used membrane housing 1
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
Used 100 % N2 and 100% H2 for testing
Cabinet temperature 255 to 257°F
Readings were taken (excluding %H2) with zero gas being fed into analyzers

STARTECH ENVIRONMENTAL CORP

Stage 1 sheet1 10-05-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | | |
| 8:45 | TURN ON ANALYZER | | | | | | | | | | |
| 9:50 | CAL. W/ SPAN & ZERO | | | | | | | | | | |
| 10:17 | START 100%N2 FLOW TO MEMBRANE 3 AT 0.8 LPM | | | | | | | | | | |
| 10:21 | 99.9 | 58.8 | 100.1 | 47.2 | 0.8 | 0.1 | 0.41 | 0 | - | | |
| 10:35 | 99.8 | 57.8 | 100.0 | 49.5 | 0.9 | 0.1 | 0.41 | 0 | | | |
| 10:46 | 99.8 | 56.9 | 100.0 | 50.2 | 0.8 | 0.1 | 0.41 | 0 | | | |
| 11:05 | 99.8 | 55.8 | 100.0 | 50.8 | 0.8 | 0.1 | 0.40 | 0 | | | |
| 11:07 | CHANGE 100% N2 FLOWRATE TO 1.4 LPM | | | | | | | | | | |
| 11:17 | 99.8 | 53.7 | 99.9 | 52 | 1.4 | 0.1 | 0.4 | 0 | | | |
| 11:34 | 99.8 | 52.8 | 100.0 | 53.6 | 1.4 | 0.1 | 0.4 | 0 | | | |
| 12:08 | 99.8 | 52.01 | 100.0 | 55.9 | 1.4 | 0.1 | 0.41 | 0 | | | |
| 12:27 | 99.8 | 51.9 | 100.0 | 56.7 | 1.5 | 0.1 | 0.41 | 0 | | | |
| 12:29 | CHANGE 100% N2 FLOWRATE TO 0.4 LPM | | | | | | | | | | |
| 12:31 | 99.9 | 54.0 | 100.2 | 56.00 | 0.4 | 0.1 | 0.41 | | | | |
| 12:50 | 99.9 | 56.0 | 100.1 | 54.2 | 0.4 | 0.1 | 0.41 | | | | |
| 1:14 | 99.9 | 57.1 | 100.1 | 53.00 | 0.5 | 0.1 | 0.42 | | | | |
| 1:21 | 99.9 | 57.2 | 100.1 | 52.8 | 0.5 | 0.1 | 0.42 | | | | |
| 1:25 | CAL. TO SPAN | | | | | | | | | | |
| 1:27 | CHANGE TO 100% H2 AT A FLOWRATE OF 0.8 LPM | | | | | | | | | | |
| 1:37 | 98.9 | 47.4 | 99.1 | 49.9 | 0.7 | 0.1 | 4.20 | 85 | 100 | | |
| 1:59 | 99.2 | 40.4 | 99.4 | 47.0 | 0.7 | 0.1 | 4.22 | 100 | 100 | | |
| 2:26 | 99.2 | 35.8 | 99.5 | 45.7 | 0.8 | 0.1 | 4.25 | 100 | 100 | | |
| 2:41 | 99.4 | 34.7 | 99.6 | 45.5 | 0.8 | 0.1 | 4.26 | 100 | 100 | | |
| 2:43 | CHANGE TO 100% H2 AT A FLOWRATE OF 1.6 LPM | | | | | | | | | | |
| 3:03 | 99.5 | 34.2 | 99.7 | 47.6 | 1.5 | 0.1 | 4.30 | | | | |
| 3:13 | 99.7 | 34.2 | 99.9 | 48.7 | 1.5 | 0.1 | 4.31 | | | | |

Used membrane housing 3
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
Used 100 % N2 and 100% H2 for testing
Cabinet temperature 255°F
Readings were taken (excluding %H2) with zero gas being fed into analyzers

STARTECH ENVIRONMENTAL CORP

Stage1 sheet2 10-05-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject | Cor. Perm. |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | | |
| 3:28 | 99.8 | 34.3 | 100.1 | 49.8 | 1.5 | 0.1 | 4.33 | | | | |
| 3:35 | 21:36 | 34.4 | 100.1 | 50.3 | 1.5 | 0.01 | 4.33 | | | | |
| 3:37 | CHANGE TO 100% H2 AT A FLOWRATE OF 2.4 LPM | | | | | | | | | | |
| 3:53 | 100.1 | 34.6 | 100.4 | 53.8 | 2.3 | 0.1 | 4.36 | | | | |
| 4:06 | 100.3 | 34.7 | 100.6 | 55.7 | 2.3 | 0.1 | 4.37 | | | | |
| 4:15 | 100.5 | 34.8 | 100.7 | 56.9 | 2.3 | 0.1 | 4.38 | | | | |
| 4:27 | 100.6 | 35.1 | 100.9 | 58.1 | 2.4 | 0.1 | 4.39 | | | | |

Used membrane housing 3
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
Used 100 % N2 and 100% H2 for testing
Cabinet temperature 255°F
Readings were taken (excluding %H2) with zero gas being fed into analyzers

STARTECH ENVIRONMENTAL CORP.

Stage 1 - 11-30-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Press. (PSIG) | |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | PE705 | PE706 |
| 2:45 | Set gas inlet pressure to 60 PSIG | | | | | | | | | | |
| 2:50 | 57.6 | 26.7 | 57.8 | 20.9 | 2.4 | 1.7 | 1.00 | 22 | 57 | | |
| 3:00 | 57.3 | 25.3 | 57.4 | 25.1 | 2.6 | 2.5 | 0.83 | 22 | 59 | 2.6 | |
| 3:05 | Reset inlet pressure (PE702) to 100 PSIG | | | | | | | | | | |
| 3:06 | Reset reject flowrate (FE701) to 3.5 LPM | | | | | | | | | | |
| 3:15 | 101.9 | 22.6 | 102.1 | 34.6 | 3.7 | 5.4 | 1.59 | 20 | 64 | 5.6 | |
| 3:23 | 102.6 | 21.5 | 102.9 | 38.7 | 3.6 | 5.2 | 1.59 | 20 | 64 | 5.6 | |
| 3:35 | 102.1 | 20.8 | 102.0 | 42.0 | 3.5 | 7.3 | 1.52 | 21 | 65 | 7.6 | |
| 3:50 | 102.5 | 20.4 | 102.7 | 44.2 | 3.5 | 9.6 | 1.50 | 23 | 64 | 10.0 | |
| 3:55 | 102.3 | 20.2 | 102.5 | 45.0 | 3.4 | 6.5 | 1.56 | 22 | 66 | 6.7 | |
| 4:05 | 101.9 | 20.1 | 102.0 | 45.8 | 3.3 | 8.3 | 1.48 | 23 | 65 | 8.8 | |
| 4:15 | 102.4 | 20.0 | 102.6 | 46.6 | 3.2 | 6.0 | 1.57 | 22 | 65 | 6.1 | |
| 4:30 | 101.7 | 20.6 | 101.9 | 46.9 | 3.5 | 9.0 | 1.48 | 24 | 65 | 9.2 | |
| 4:34 | Ran feed gas through gas analyzer to confirm %H: 35% H2 | | | | | | | | | | |
| 4:35 | Shutdown system | | | | | | | | | | |

Used membrane housing 1 & 3
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
During testing, pressure (PE702) and flow (FE701) were set and monitored
Recorded pressures and flows with analyzer measuring zero gas
Used PCG for feed gas. Feed stream into PC was surrogate MSW

Stage 1 - 12-01-05

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Press. (PSIG) | |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | PE705 | PE706 |
| 2:00 | Start gas flow | | | | | | | | | | |
| 2:01 | Reset inlet pressure (PE702) to 100 PSIG | | | | | | | | | | |
| 2:02 | Reset reject flowrate (FE701) to 3.5 LPM | | | | | | | | | | |
| 2:05 | 100.1 | 26.7 | 100.2 | 22.8 | 3.5 | 6.4 | 1.88 | 25 | 61 | 6.4 | |
| 2:28 | 99.5 | 22.2 | 99.6 | 37.7 | 3.3 | 6.0 | 1.60 | 20 | 64 | 6.1 | |
| 2:42 | 100.1 | 20.6 | 100.1 | 42.8 | 3.2 | 9.0 | 1.55 | 23 | 64 | 8.9 | |
| 2:55 | 99.4 | 19.9 | 99.4 | 45.5 | 3.2 | 7.5 | 1.54 | 23 | 64 | 7.5 | |
| 3:08 | 99.8 | 19.7 | 99.8 | 47.2 | 3.3 | 9.9 | 1.48 | 24 | 63 | 9.9 | |
| 3:29 | 99.8 | 19.5 | 99.9 | 48.8 | 3.3 | 8.8 | 1.50 | 24 | 64 | 8.8 | |
| 3:57 | 99.5 | 19.6 | 99.5 | 49.2 | 3.2 | 8.9 | 1.45 | 23 | 63 | 8.9 | |
| 4:11 | 100.1 | 19.5 | 100.1 | 49.3 | 3.3 | 7.3 | 1.50 | 23 | 63 | 7.3 | |
| 4:15 | Shutdown system | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | Final pressure readings | | | | | | | | | | |
| | TK701 | 142.1 PSIG | | | | | | | | | |
| | TK702 | 55.5 PSIG | | | | | | | | | |
| | TK703 | 8.0 PSIG | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

Used membrane housing 1 & 3
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
During testing, pressure (PE702) and flow (FE701) were set and monitored
Recorded pressures and flows with analyzer measuring zero gas
Used PCG for feed gas. Feed stream into PC was surrogate MSW

STARTECH ENVIRONMENTAL CORP

Stage 1 - 01-11-06

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Input PCG | |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | %H2 | |
| 11:00 | Calibrate analyzer with zero and span gas | | | | | | | | | | |
| 12:24 | Purged stage 1 compressed gas tank (TK701) twice by releasing from 150 psig to 100 psig, refilling to 150 psig, draining to 100 psig, | | | | | | | | | | |
| | then refilling again. Opened valves to allow PCG to membranes at 12:24. Membranes 1, 3 & 4 all feeding stage 2 (TK702) w/ permeate. | | | | | | | | | | |
| | Will fill stage 2 compressor tank (TK703) prior to switching mod. 4 to stage 2. | | | | | | | | | | |
| 12:28 | 100.5 | 31.4 | 100.7 | 21.1 | 0.0 | 3.8 | 1.24 | 12 | 50 | | |
| | Increase reject flow to 0.5 LPM to get a reading | | | | | | | | | | |
| 12:34 | 100.0 | 29.9 | 100.2 | 23.1 | 0.5 | 4.7 | 1.41 | 10 | 52 | 34.0 | |
| | H2 input gas from PCG 34-35% H2 | | | | | | | | | | |
| 12:46 | 100.0 | 27.5 | 100.2 | 25.3 | 0.5 | 7.1 | 1.37 | 16 | 54 | | |
| 13:02 | 99.7 | 27.0 | 99.9 | 27.0 | 0.5 | 6.8 | 1.36 | 13 | 52 | | |
| 13:21 | 99.9 | 27.2 | 100.1 | 29.1 | 0.5 | 5.8 | 1.37 | 14 | 54 | 35.1 | |
| 13:45 | 99.7 | 27.7 | 99.8 | 30.7 | 0.5 | 5.8 | 1.35 | 13 | 52 | | |
| 13:53 | Increase reject flowrate to 1.5 LPM | | | | | | | | | | |
| 14:07 | 99.5 | 25.6 | 99.7 | 33.4 | 1.5 | 5.7 | 1.53 | 19 | 61 | 34.8 | |
| 14:31 | 99.0 | 24.5 | 99.2 | 35.7 | 1.4 | 8.8 | 1.46 | 19 | 60 | | |
| 14:53 | 99.3 | 24.3 | 99.4 | 36.7 | 1.5 | 8.9 | 1.45 | 20 | 60 | | |
| 15:07 | 99.1 | 24 | 99.3 | 37.2 | 1.4 | 7 | 1.46 | 18 | 61 | | |
| 15:11 | Reduce reject flowrate to 1.0 LPM | | | | | | | | | | |
| 15:19 | 99.7 | 24.7 | 99.9 | 36.7 | 1 | 9.3 | 1.35 | 17 | 57 | | |
| 15:46 | 99.3 | 25.7 | 99.5 | 35.4 | 0.9 | 5.8 | 1.39 | 16 | 57 | 35 | |
| 16:01 | 99.8 | 26.2 | 100.1 | 35 | 1 | 8.1 | 1.37 | 16 | 57 | | |
| 16:12 | 99.7 | 26.1 | 99.9 | 34.7 | 0.9 | 5.8 | 1.4 | 17 | 59 | | |
| 16:28 | Test %H2 of PCG using 1st stage reject & close permeate valve 35% | | | | | | | | | | |
| 16:34 | Stop gas feed to stage 1. | | | | | | | | | | |
| | Cabinet temperature is 125°C | | | | | | | | | | |
| | | | | TK701 | TK702 | TK703 | | | | | |
| 16:34 | Pressure in starcell tanks (PSIG) | | | 138.6 | 8.1 | 57.0 | | | | | |
| 8:46 | (1/12/06) | | | 137.0 | 7.8 | 54.5 | | | | | |

Used membrane housings 1, 3 & 4
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
During testing, pressure (PE702) and flow (FE701) were set and monitored
Recorded pressures and flows with analyzer measuring zero gas
Used PCG for feed gas. Feed stream into PC was surrogate MSW
When measuring %H2, analyzer flowmeter settings for reject and permeate were 4.5 and 4.0 LPM, respectively

STARTECH ENVIRONMENTAL CORP

Stage 1 - 01-12-06

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Input PCG | |
| | PE702 | TE702 | PE703 | TE703 | FE701 | PE704 | FE702 | | | %H2 | |
| 10:45 | Calibrate analyzer with zero and span gas | | | | | | | | | | |
| 12:37 | Test %H2 in PCG gas using 1st stage reject and close permeate valve 35% | | | | | | | | | | |
| 12:43 | Set reject flowrate at 2.0 LPM | | | | | | | | | | |
| 12:49 | 99.8 | 28.7 | 100.0 | 27.8 | 2.1 | 6.7 | 1.64 | 19 | 64 | 35.5 | |
| 13:07 | 100.3 | 24.5 | 100.4 | 32.5 | 1.9 | 6.1 | 1.62 | 18 | 63 | | |
| 13:25 | 100.6 | 23.3 | 100.8 | 36.9 | 2.0 | 9.6 | 1.52 | 20 | 63 | 35.9 | |
| 13:29 | Open valve to feed hot oil to 2nd stage HX | | | | | | | | | | |
| 13:43 | 100.1 | | 100.3 | 39.4 | 2.0 | 8.9 | 1.52 | 21 | 63 | | |
| 13:57 | 100.5 | 27.5 | 100.7 | 39.6 | 1.9 | 7.1 | 1.57 | 20 | 63 | | |
| 14:12 | 100.5 | 27.0 | 100.3 | 38.0 | 1.9 | 5.5 | 1.54 | 20 | 61 | 37.5 | |
| 14:42 | 100.1 | 27.2 | 100.3 | 40.3 | 2.0 | 7.4 | 1.53 | 20 | 62 | | |
| 15:04 | 100.2 | 27.7 | 100.4 | 41.7 | 2.2 | 7.6 | 1.54 | 22 | 64 | | |
| 15:07 | Switch membrane 4 to stage 2 | | | | | | | | | | |
| 15:34 | 100.2 | 25.6 | 100.4 | 41.2 | 2.2 | 8.6 | 1.30 | 26 | 63 | 35.5 | |
| 15:36 | Drop reject flow rate to 1.3 LPM | | | | | | | | | | |
| 15:55 | 100.2 | 24.3 | 100.4 | 36.9 | 1.3 | 7.8 | 1.28 | 21 | 60 | | |
| 16:05 | 100.9 | 24 | 101.1 | 34.6 | 1.2 | 9.2 | 1.25 | 22 | 60 | | |
| 16:14 | 101.0 | | 101.2 | 33.5 | 1.0 | 6.3 | 1.3 | 21.0 | 59.0 | | |
| 16:24 | 100.8 | 24.7 | 101 | 33 | 1.2 | 8 | 1.27 | 21 | 59 | | |
| 16:34 | 100.9 | 25.7 | 101 | 33.3 | 1.3 | 9.5 | 1.24 | 22 | 59 | | |
| 16:44 | 100.6 | 26.2 | 100.7 | 33.7 | 1.3 | 6.9 | 1.29 | 22 | 59 | | |
| 17:10 | Test H2% in feed by measuring reject and closing permeate valve 39.5 | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

Used membrane housings 1, 3 & 4 until 15:07
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
During testing, pressure (PE702) and flow (FE701) were set and monitored
Recorded pressures and flows with analyzer measuring zero gas
Used PCG for feed gas. Feed stream into PC was surrogate MSW
When measuring %H2, analyzer flowmeter settings for reject and permeate were 4.5 and 4.0 LPM, respectively

STARTECH ENVIRONMENTAL CORP

Stage 2 - 01-12-06

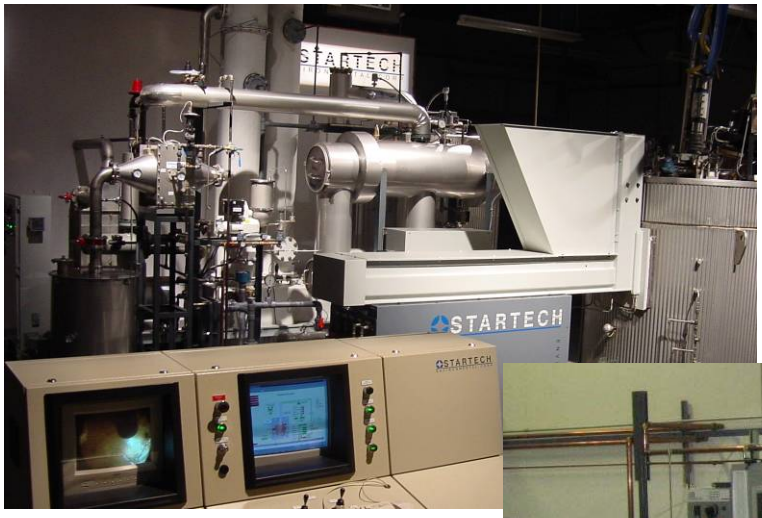
| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Press. (PSIG) | Temp. (°C) | Flow (LPM) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor. Reject | Cor. Perm. |
| | PE707 | TE705 | PE708 | TE706 | FE703 | PE709 | FE704 | | | | |
| 15:07 | Test feed gas for H2% by measuring reject and closing permeate valve 54% | | | | | | | | | | |
| 15:38 | Try to maintain reject flowrate of 0.8 LPM and Permeate pressure of ~15 PSIG | | | | | | | | | | |
| 15:42 | 84.9 | 19.2 | 84.2 | 38.1 | 0.81 | 6.8 | 0.24 | 44 | 80 | | |
| 15:51 | 84.5 | 18.1 | 84.4 | 37.7 | 0.78 | 15.8 | 0.25 | 46 | 83 | | |
| 15:59 | 84.6 | 17.0 | 84.5 | 37.2 | 0.74 | 15.3 | 0.21 | 46 | 80 | | |
| 16:09 | 84.3 | 16.1 | 84.1 | 37.1 | 0.78 | 16.2 | 0.20 | 45 | 79 | | |
| 16:19 | 84.5 | 15.7 | 84.3 | 37.1 | 0.77 | 16.1 | 0.25 | 44 | 79 | | |
| 16:29 | 84.3 | 15.6 | 84.2 | 37.3 | 0.76 | 15.0 | 0.23 | 44 | 79 | | |
| 16:39 | 84.6 | 15.7 | 84.5 | 38.2 | 0.77 | 14.8 | 0.23 | 44 | 79 | | |
| 16:49 | 84.1 | 15.6 | 84.1 | 39.0 | 0.77 | 14.9 | 0.24 | 44 | 79 | | |
| 16:52 | Set reject flowrate to 0.23 LPM | | | | | | | | | | |
| 16:57 | 85.1 | 16.1 | 85.0 | 38.0 | 0.23 | 13.3 | 0.19 | 45 | 77 | | |
| 17:04 | 85.5 | 16.5 | 85.4 | 37.7 | 0.23 | 12.3 | 0.17 | 42 | 76 | | |
| 17:27 | Test feed gas for H2% by measuring reject and closing permeate valve 52% | | | | | | | | | | |

Used membrane housing 4
Used 100 % N2 and 100% H2 for zero and span gas (respectively) prior to testing
Recorded pressures and flows with analyzer measuring zero gas
Used PCG for feed gas. Feed stream into PC was surrogate MSW
When measuring %H2, analyzer flowmeter settings for reject and permeate were 4.0 and 2.5 LPM, respectively
Starcell cabinet temperature was 119°C at 16:39

STARTECH ENVIRONMENTAL CORP.

U.S. Department of Energy
Energy Efficiency and Renewable Energy

# Startech Hydrogen Production
# Phase 2 Final Technical Report
# July 2007




**Prepared for:**

Department of Energy
Golden Field Office
1617 Cole Boulevard
Golden, Colorado 80401-3393
Award No: DE-FC36-04GO14233

# Table of Contents

### 7.5. List of Accomplishments

## 8. Conclusion and Discussion

## Appendices

**Appendix A:** **StarCell Data Sheets**

**Appendix B:** **Results Summary Calculations**

**Appendix C:** **StarCell Process Flow Diagram**

**Appendix D:** **Process Photos**

**List of tables and figures:**

## 1.0 Program Objectives

The purpose of this project is to evaluate viability of integrated hydrogen production from waste materials using a Plasma Converter and a StarCell™ multistage-ceramic membrane hydrogen separation system. Specifically, this project will achieve the following:

- Field test integrated hydrogen production on a pilot scale using plasma gasification and ceramic membrane hydrogen separation.
- Evaluate commercial viability and scalability through extended operation under representative conditions.
- Characterize the performance of the integrated Plasma Converter and StarCell™ Systems for hydrogen production and purification from abundant and inexpensive feedstocks.
- Compare integrated hydrogen production performance to conventional technologies and DOE benchmarks.
- Run pressure and temperature testing to baseline StarCell's performance.
- Determine the effect of process contaminants on the StarCell™ system.

## 2.0 Test Overview

There were three main aspects to the Phase 2 testing performed:

- Baseline characterization and adjustment / optimization of the performance of the reconfigured StarCell™ Multistage Ceramic Membrane System,
- Gasification of municipal solid waste (MSW) feedstock with the Plasma Converter System™ (PCS), and
- Separation of hydrogen from the resultant gas using the StarCell™.

Testing focused on hydrogen separation through the Membrane system from both bottled gas mixtures as well as from synthesis gas generated from plasma conversion of a MSW surrogate feedstock.

Processing took place at the Startech Engineering Research and Demonstration Facility at 190 Century Drive, Bristol, Connecticut, USA. Startech personnel operated the system for the Program. Phase 2 test data was collected via process instrumentation and online analysis.

## 3.0 StarCell System Information

### *3.1 StarCell Phase 2 System Description*

The StarCell System design underwent several configuration changes in preparation for the Phase 2 testing. Figures 3.1 shows a 3D model of the Phase 1 StarCell cabinet that essentially worked as a hot oil heated oven to maintain the gas and membrane temperatures. The gas was also pre-heated prior to entering the cabinet. Despite heating capabilities of the system, the ability to operate at higher temperature was identified as a primary area of improvement coming out of Phase 1 testing. The majority of the changes implemented in Phase 2 focused on improved heating of the gas at the membrane.

**Figure 3.1**: Phase 1 Membrane and Heater Configuration

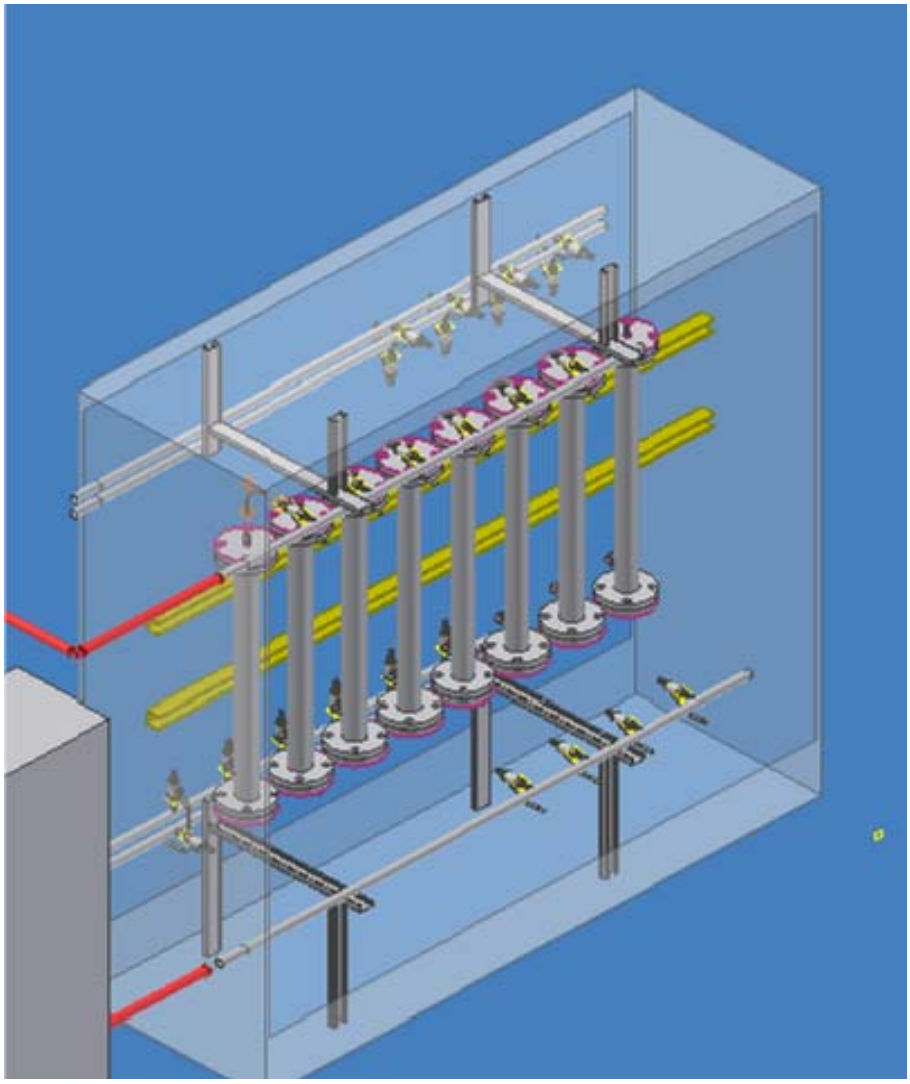


**Figure 3.2**: Phase 2 Membrane and Heater Configuration

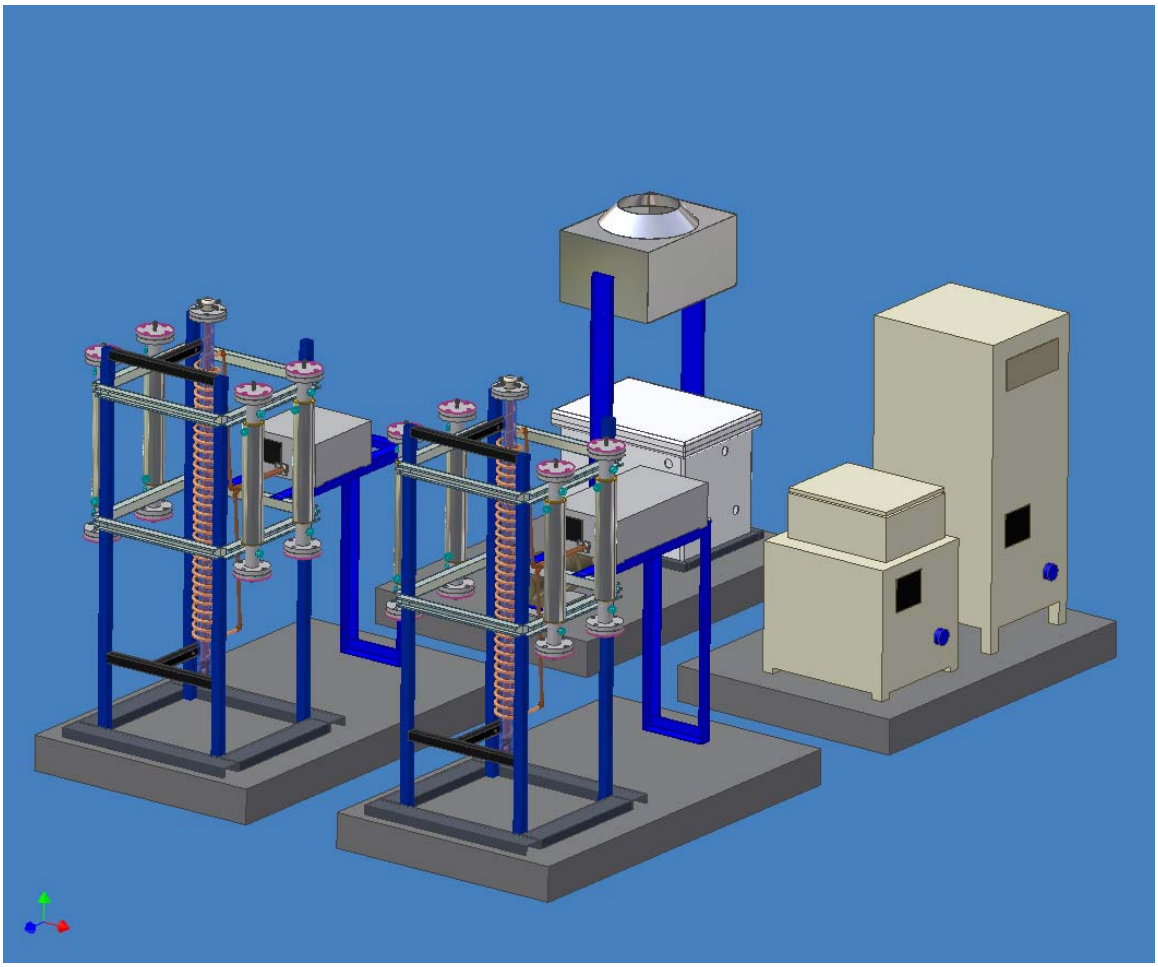


Figure 3.2 shows a 3D model of the Phase 2 StarCell module and heating system configuration. The primary objective of the StarCell design modifications for Phase 2 testing was to allow maximum parametric flexibility during operation. Energy optimization of the system would be addressed in future designs once optimal process conditions and system capability are characterized. Instrumentation on the StarCell provides continuous process data such as temperatures, pressures, flows, and gas composition at points of interest in the purification system. StarCell was constructed to accommodate tubular membranes bundled together in modules, though planar stacks and other configurations could easily be incorporated.

**Figure 3.3:** StarCell Process Flow Diagram

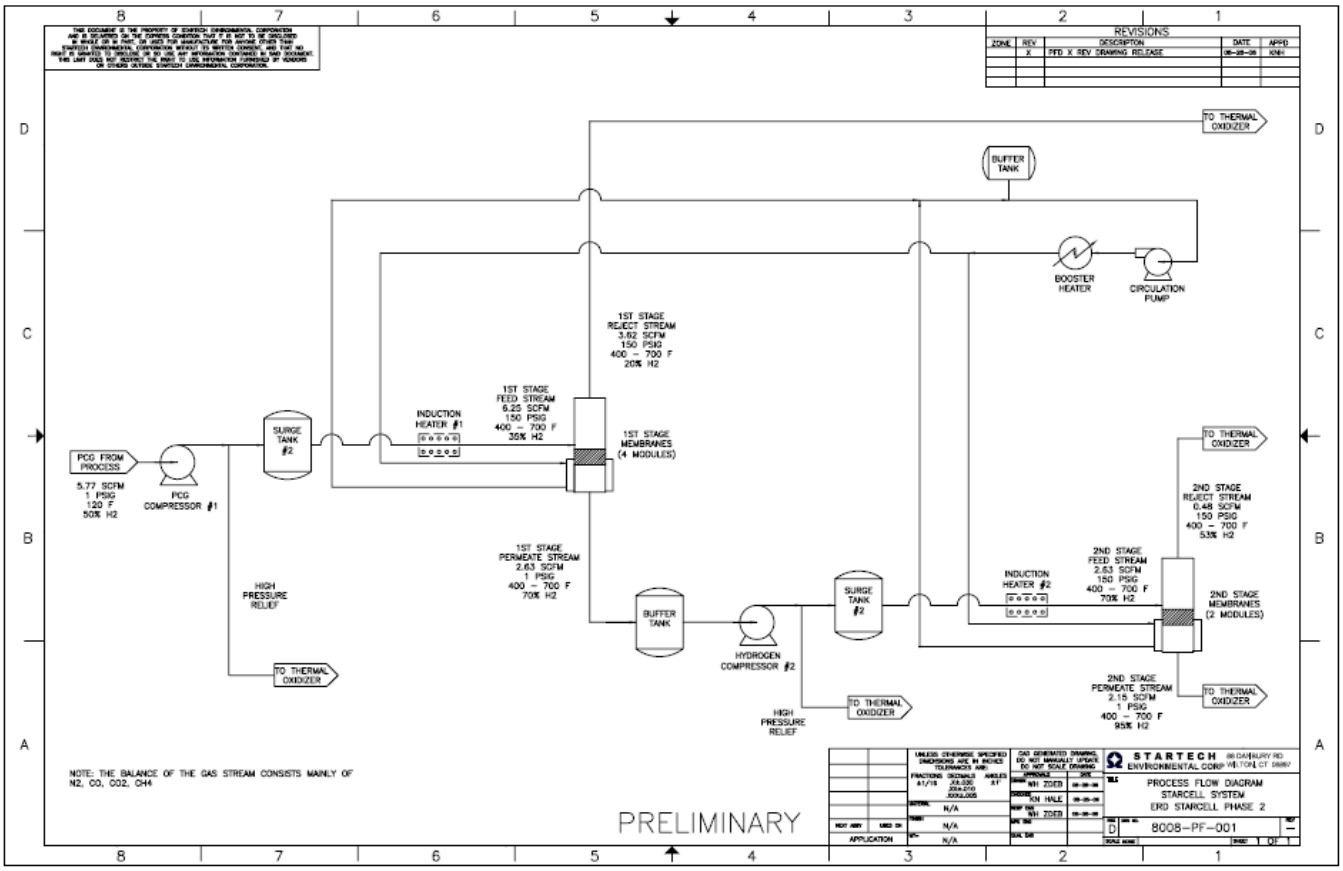



Figure 3.3 shows a Process Flow Diagram of the StarCell System. A larger print copy of this sheet can be found in Appendix C of this report. Hydrogen rich gas is fed into the stage 1 compressor and then stored in Surge Tank #1. If the feed gas is already compressed (i.e. for bottled gas testing), then the compressor can be bypassed. The pressure regulated feed gas passes through an induction coil heat exchanger to heat the gas before flowing to the first stage of membranes for purification. The membrane housings are jacketed with hot oil to help maintain the gas temperature throughout the membrane. Gas flow through the stage 1 membranes is regulated by a needle valve on the reject side of the membranes and by the permeance of the membranes themselves. The stage 1 permeate flows to a permeate buffer tank. When the permeate buffer tank reaches a pressure set point, the stage 2 compressor pumps down the permeate from the Buffer Tank to a higher pressure tank (Surge Tank #2) that is used to feed stage 2 membranes. Gas flow from Surge Tank #2 is again pressure regulated and passes through a heat exchanger prior to introduction to the stage 2 membranes. Alternatively, the permeate Buffer Tank, stage 2 compressor, and Surge Tank #2 can

be bypassed altogether allowing the permeate from stage 1 to flow directly through the heat exchanger to the stage 2 membranes.

*3.2 StarCell Instrumentation and Controls*

3.2.1 The following is a list of instrumentation used directly in the StarCell hydrogen separation process and performance evaluation.

**Table 3.1**: Instrumentation list for Phase 2 StarCell Hydrogen separation performance evaluation.

| Device ID | Type | Description |
|---|---|---|
| PT701 | Pressure Transducer | First stage feed gas tank pressure. This is the pre-regulated pressure in psig available to stage 1 membranes from the stage 1 compressor. |
| PT702 | Pressure Transducer | First stage line pressure. This is the post regulated pressure in psig of the gas being fed to the stage 1 membranes. This is representative of the pressure that the membranes are seeing. |
| TE 714 | Thermocouple | This is the skin temperature of the Stage 1 induction heater that the gas passes through immediately prior to the membrane. Measurement units are in degrees Celsius. This device is meant as a safety device to ensure that the contact temperature stayed below the auto-ignition temperature of Hydrogen (571°C). |
| TE702 | Thermocouple | This is the gas temperature in °C measured at the top of the induction heater manifold prior to being split off to the individual membrane modules. This is the closest approximation of the gas input temperature. |
| TE703 | Thermocouple | This is the gas temperature in °C on the reject gas line after the membrane module. This thermocouple was located at the junction of the first stage membrane module reject gas lines to yield a composite gas temperature of all the stage 1 membranes. |
| PT703 | Pressure Transducer | This is the stage 1 reject line gas pressure in psig located immediately prior to the needle valve that controls the reject side flow. In most cases this pressure reading is reflective of the stage 1 membrane module input pressure. |

**Table 3.1**: Instrumentation list for Phase 2 StarCell Hydrogen separation performance evaluation. (cont.)

| Device ID | Type | Description |
|---|---|---|
| FIT 701* | Mass Flow Meter | FIT 701 measures the mass flow of the reject side gas in standard liters per minute. The device is calibrated for 0 – 30 slpm of:<br>34% $H_2$<br>12% $N_2$<br>46% CO<br>7% $CO_2$ |
| TE709 | Thermocouple | This is the gas temperature in °C on the permeate gas line after the membrane module. This thermocouple was located at the junction of the first stage membrane module permeate gas lines to yield a composite gas temperature of all the stage 1 permeate gas. |
| PT704 | Pressure Transducer | This is the permeate line gas pressure in psig located immediately after the stage 1 membrane modules. In most cases this pressure reading is reflective of PT705, the low-pressure surge tank pressure. |
| FIT702* | Mass Flow Meter | FIT 701 measures the mass flow of the permeate side gas in standard liters per minute. The device is calibrated for 0 – 10 slpm of Hydrogen. |
| PT705 | Pressure Transducer | This is the gas pressure in psig of the stage 1 surge tank used to collect stage 1 permeate gas. This pressure is the control pressure that triggers the stage 2 compressor to pump down the stage 1 permeate into the stage 2 feed tank and ensures that the stage 2 compressor does not pump against a vacuum. |
| PT706 | Pressure Transducer | Second stage feed gas tank pressure. This is the pre-regulated pressure in psig available to stage 2 membranes from the stage 2 compressor. |
| PT707 | Pressure Transducer | This is the post-regulated pressure in psig of the gas being fed to the stage 2 membranes. This is representative of the pressure that the membranes are seeing. |
| TE 715 | Thermocouple | This is the skin temperature of the Stage 2 induction heater that the gas passes through immediately prior to the membrane. Measurement units are in degrees Celsius. This device is meant as a safety device to ensure that the contact temperature stayed below the auto-ignition temperature of Hydrogen (571°C). |

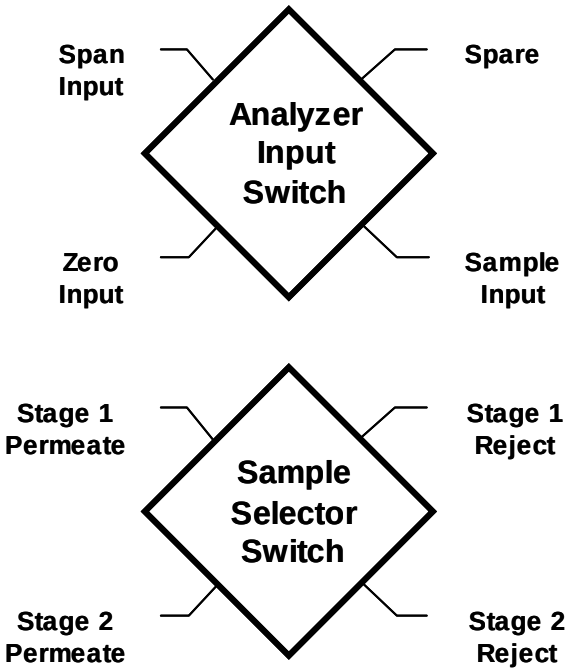
**Table 3.1**: Instrumentation list for Phase 2 StarCell Hydrogen separation performance evaluation. (cont.)

| Device ID | Type | Description |
|---|---|---|
| TE705 | Thermocouple | This is the gas temperature in °C measured at the top of the induction heater manifold prior to being split off to the individual membrane modules. This is the closest approximation of the stage 2 gas input temperature to the modules. |
| TE706 | Thermocouple | This is the gas temperature in °C on the reject gas line after the membrane module. This thermocouple was located at the junction of the second stage membrane module reject gas lines to yield a composite gas temperature of all the stage 2 membranes. (As Stage 2 used only 1 membrane module, the thermocouple was located directly at the bottom of the membrane module.) |
| PT709 | Pressure Transducer | This is the stage 2 reject line gas pressure in psig located immediately prior to the needle valve that controls the reject side flow. In most cases this pressure reading is reflective of the stage 2 membrane module input pressure. |
| FIT 703* | Mass Flow Meter | FIT 703 measures the mass flow of the reject side gas in standard liters per minute. The device is calibrated for 0 – 5 slpm of:<br>83% $H_2$<br>17% CO |
| TE710 | Thermocouple | This is the gas temperature in °C on the permeate gas line after the stage 2 membrane module(s). This thermocouple was located at the junction of the second stage membrane module permeate gas lines to yield a composite gas temperature of all the stage 2 permeate gas. (As Stage 2 used only 1 membrane module, the thermocouple was located directly at the outlet of the permeate.) |
| PT708 | Pressure Transducer | This is the permeate line gas pressure in psig located immediately after the stage 2 membrane modules. |
| FIT704* | Mass Flow Meter | FIT 701 measures the mass flow of the permeate side gas in standard liters per minute. The device is calibrated for 0 – 10 slpm of Hydrogen. |

### 3.2.2 Hydrogen Analysis:

Helium and Hydrogen in all streams of the StarCell system were analyzed using a Thermal Conductivity Analyzer. In order to use a single analyzer for all gas streams, a switching manifold was constructed. Two separate 4 way valves were configured as shown in Figure 3.4 below:

**Figure 3.4:** Sample selection manifold configuration

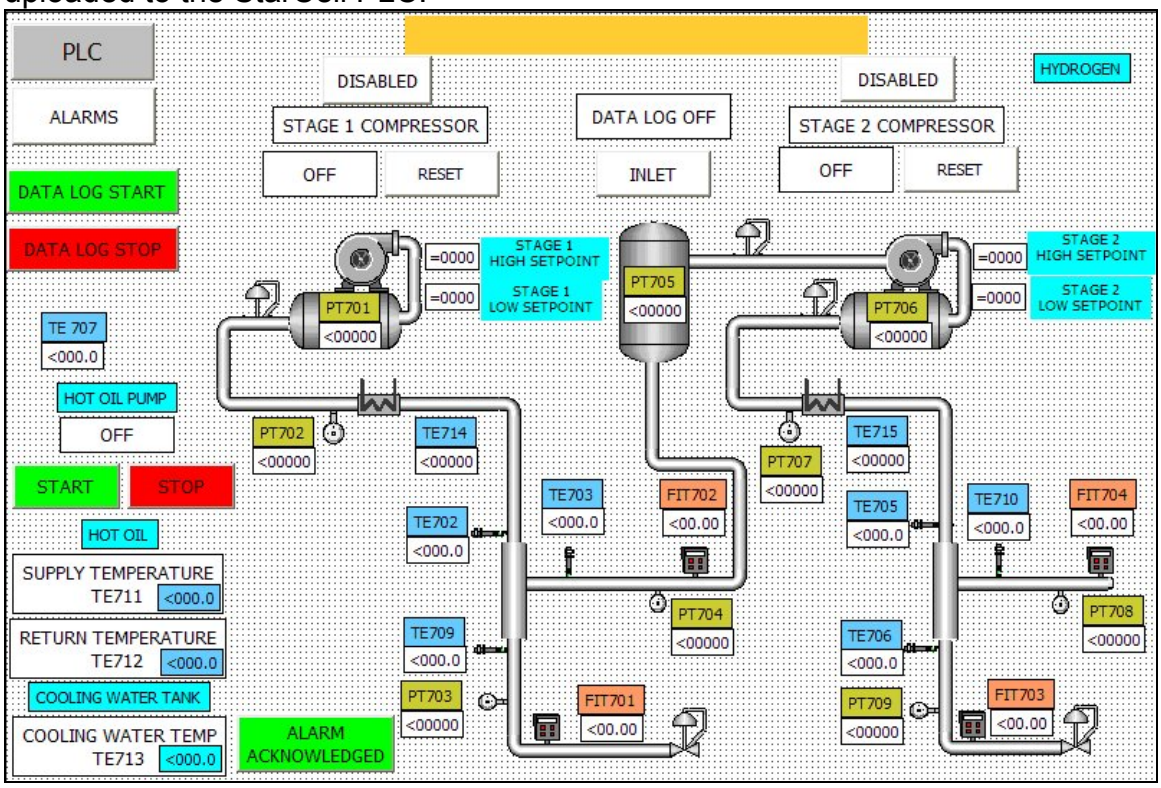



The analyzer input valve selected which feed went to the analyzer. When the valve was in the Sample input position, the Sample selector switch governed which sample was fed to the analyzer.

### 3.2.3 StarCell Controls:

The StarCell system was operated using a Seimens PLC with an integrated touch screen. Manual control inputs were primarily limited to pressure and temperature set points. The PLC performed safety functions such as interlocking heaters and compressors with temperature and pressure set points. The PLC also sent data to a computer to be logged and gave a real-time display of the current readings of the StarCell instrumentation. Membrane module performance was governed primarily by the input gas pressure, and reject flow which were controlled manually. Figure 3.4 shows the control screen layout.

**Figure 3.5:** StarCell Control Screen: This is the control screen prior to being uploaded to the StarCell PLC.




### 3.2.4 Membrane Module Information:

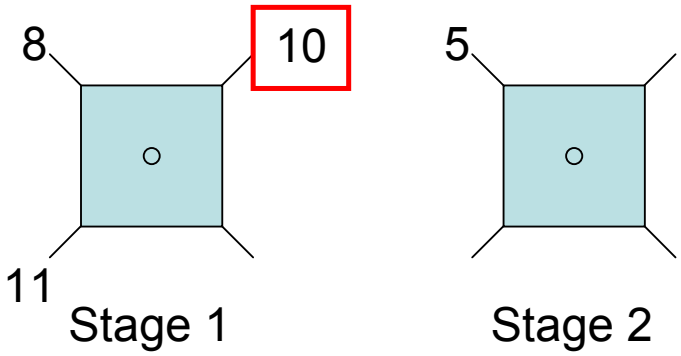
Prior to being shipped to Startech, the membrane modules were tested at Media and Process Technologies (M&PT) for leakage and permeance with single component gases. Performance and quality data provided to Startech Environmental Corporation by M&PT on these membrane modules is shown in Table 3.2.

**Table 3.2:** Media and Process Technology Phase 1 Module Quality Data

| | Permeance @ 120°C [m3/m2/hr/bar] | | Selectivity |
|---|---|---|---|
| **Membrane ID** | **He** | **$N_2$** | **He/$N_2$** |
| Bundle 5 | 0.436 | 0.013 | 34.5 |
| Bundle 8 | 0.243 | 0.007 | 36.4 |
| Bundle 10 | 0.383 | 0.012 | 33.0 |
| Bundle 11 | 0.376 | 0.010 | 38.3 |

The above data was taken on individual tubes. The results were then averaged to obtain the reported Permeance and selectivity data. Effects of downstream processes such as membrane potting shipping, shelf time, and installation into StarCell system may have had unquantified effects on the module performance measured at Startech. Figure 3.6 shows the membrane layout as it was installed in the StarCell system.

**Figure 3.6:** StarCell Module Layout




Module # 10 was not used due to a leak in the module housing
Stage 1 used Modules 11 and 8
Stage 2 used Module 5

## 4.0 StarCell Shakedown Testing

### *4.1 Objectives:*

4.1.1 To confirm proper function and safe operation of the StarCell system with inert contents.
4.1.2 To characterize basic StarCell operation and responsiveness of the system using an inert gas mixture.
4.1.3 Compare results of StarCell System instrumentation with laboratory quality control information using Helium and Nitrogen.
4.1.4 Determine reasonable parametric limits to be used in optimization testing.
4.1.5 Compare Phase 2 membrane module configuration performance with Phase 1 Membrane module performance

### *4.2 Test Description:*

4.2.1 Test Summary: During this test, an inert mixture of Helium and Nitrogen was run through the StarCell system. Control

parameters were spanned to both verify the operability of the system subcomponents and to determine their effective range.

4.2.2 Data and Analysis: Data obtained from the StarCell system I includes gas flows, gas temperatures, and pressures, operation times, parameter changes, and observations of the system operation. Internal analysis was performed on the gas stream to determine helium content after Stage 1 and after Stage 2.

4.2.3 External Testing: The inert gas mixture was tested for composition by a third party laboratory prior to use in the StarCell.

*4.3 Results and Discussion:*

The focus of the shakedown test was to ensure proper operation of the StarCell while processing inert materials. A Blend of 50% helium, balance Nitrogen was used as the inert test mixture. Table 4.1 shows comparative data from Phase 1 testing last year and an excerpt of the Phase 2 testing from April of this year.

**Table 4.1:** Phase 1 and Phase 2 Shakedown Tests; Summary of Test Conditions

| **Stage 1 He and $N_2$ separation:** | **Phase 1** | **Phase 2** | **Units** |
|---|---|---|---|
| Test Gas He input: | 50% | 50% | % |
| Test Gas Temperature (Reject): | 50 | 44.48 | °C |
| Feed pressure: | 100 | 95.3 | psig |
| Feed Partial Pressure He: | 50 | 47.65 | psi |
| Permeate Pressure: | 45 | 6.8 | psig |
| Permeate side gas composition (%): | 79% | 95% | % |
| Permeate Partial Pressure He: | 35.6 | 6.4858 | psi |
| H2 Partial Pressure Diff: | 14.5 | 41.164 | psi |
| Membrane surface area: | 0.304 | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 1.9 | 16.844 | lpm |
| Total He to membrane: | 0.95 | 8.422 | lpm |
| Permeate gas flow: | 0.6 | 6.68 | lpm |
| Recovery rate: | 50% | 76% | % |
| Permeance: | 0.094 | 0.432 | $m^3/m^2/hr/bar$ |
| Flux: | 0.43 | 1.95 | scfh/sf |

While the conditions under which the two tests were run were not identical (Permeate side pressure was different for the two tests), they were close

enough to show significant differences in performance that were consistent throughout the Phase 2 testing. While some of this had to do with improved process conditions such as higher temperature and pressure, it was clear from the start that the new generation of membrane modules used in Phase 2 testing was a significant improvement over those used in Phase 1 testing. Of particular interest is the fact that the flow of Helium was about 10 times more than in the initial testing and of higher quality. This was due in part to the higher differential pressure across the membrane, which contributed to about 2- 3 times the flow, but more importantly, the flux and permeance of the membrane module itself was about 4 -5 times better than the modules used in Phase 1 testing.

Shakedown testing included experimentation to characterize the system in preparation for testing with hydrogen gas. An example of the type of experimentation we did was an evaluation of how and when to pull sample gas through the analyzer with minimum impact to the steady state conditions and the composition. It was found that all flow, pressure, and temperature data should be taken first, then the permeate gas should be measured, then the reject gas. Also, the reject gas hydrogen content measurement was always taken as a minimum because the additional flow of the reject gas was enough to skew the hydrogen content to the high side as the membranes would not be able to pull the additional hydrogen (or helium) out of the extra sample gas.

Another shakedown experiment that was done was evaluating the membrane performance under constant conditions varying only the inlet pressure. Theoretically, as the flux equation normalizes for differential pressure, operation at different pressure should yield the same flux. The data in table 4.1 clearly shows that membrane performance is dependent on the input pressure of the gas being fed to the membrane despite the fact that flux and permeance terms account for differential pressure. This relationship was discussed in further detail in the Analysis section of this report.

**Table 4.2:** Stage 2 Pressure Comparison Data

| **Stage 2 He and $N_2$ separation:** | **40 psig** | **80 psig** | **Units** |
|---|---|---|---|
| Test Gas He input: | 50% | 50% | % |
| Test Gas Temperature (Reject): | 64.091 | 50.136 | °C |
| Feed pressure: | 42.254 | 80.096 | psig |
| Feed Partial Pressure He: | 21.127 | 40.048 | psi |
| Permeate Pressure: | 5.9312 | 12.993 | psig |
| Permeate side gas composition (%): | 82% | 83% | % |
| Permeate Partial Pressure He: | 4.8587 | 10.823 | psi |
| H2 Partial Pressure Diff: | 16.268 | 29.225 | psi |
| Membrane surface area: | 0.148 | 0.148 | $m^2$ |
| Total gas flow to membrane (lpm): | 5.2312 | 11.71 | lpm |
| Total He to membrane: | 2.6156 | 5.855 | lpm |
| Permeate gas flow: | 2.3831 | 5.7564 | lpm |
| Recovery rate: | 75% | 82% | % |
| Permeance: | 0.705 | 0.964 | $m^3/m^2/hr/bar$ |
| Flux: | 3.19 | 4.37 | scfh/sf/20 psi |

## 5.0 Hydrogen and CO Mixed Gas testing

### *5.1 Objectives*

5.1.1 To characterize basic StarCell operation and responsiveness of the system using a calibrated blend of Hydrogen and Carbon Monoxide.

5.1.2 Compare StarCell System performance with projected module performance.

5.1.3 Perform parametric testing to dial in optimal settings for hydrogen separation from CO.

5.1.4 Determine baseline system characteristics (i.e. Hydrogen recovery rate, system capacity, purity capability, multistage effectiveness)

### *5.2 Test Description:*

5.2.1 Test Summary: During this test, a mixture of Hydrogen and Carbon Monoxide was run through the StarCell system. Control parameters were tuned to determine optimal separation conditions within the StarCell System.

5.2.2 Data and Analysis: Data obtained from the StarCell system include gas flows, gas temperatures, and pressures, operation times, parameter changes, and observations of the

system operation. Internal analysis was performed on the gas stream to determine hydrogen content after Stage 1 and after Stage 2.

5.2.3 External Testing: Gas mixtures was tested for composition by a third party laboratory prior to use in the StarCell. No additional third party analysis is required.

*5.3 Results and Discussion:*

Initial Hydrogen separation testing was performed under the same conditions as the shakedown testing and under the same conditions that were run for Phase 1 mixed gas testing last year. Sample results from Phase 2 hydrogen separation are shown in Table 5.2. Results from last years testing of the same type are shown in table 5.1. The operating conditions were held more or less constant for the two sets of testing shown. The results of the this year's Phase 2 mixed gas testing showed that the membrane modules were capable of purifying the gas to 99% (purest measurable hydrogen) in two passes with recovery rates reliably above 80% and often greater than 90%.

Additional analysis of this testing is included in the Analysis section of this report. Test results and data can be found in the appendices of this report.

**Table 5.1:** Stage 1 and Stage 2 $H_2$ and CO separation from Phase 1 testing (For comparison with current results)

| **Phase 1 $H_2$ and CO separation:** | **Stage 1** | **Stage 2** | **Units** |
|---|---|---|---|
| Test Gas $H_2$ input: | 50% | 80% | % |
| Test Gas Temperature (Reject): | 50 | 60 | °C |
| Feed pressure: | 102 | 100 | psig |
| Feed Partial Pressure $H_2$: | 51 | 80 | psi |
| Permeate Pressure: | 7 | 1.2 | psig |
| Permeate side gas composition (%): | 80% | 96% | % |
| Permeate Partial Pressure $H_2$: | 5.6 | 1.2 | psi |
| $H_2$ Partial Pressure Diff: | 45.4 | 78.8 | psi |
| Membrane surface area: | 0.304 | 0.156 | $m^2$ |
| Total gas flow to membrane (lpm): | 5.6 | 2.3 | lpm |
| Total $H_2$ to membrane: | 2.8 | 1.84 | lpm |
| Permeate gas flow: | 2.8 | 1.25 | lpm |
| Recovery rate: | 80% | 65% | % |
| Permeance: | 0.141 | 0.085 | $m^3/m^2/hr/bar$ |
| Flux*: | 0.64 | 0.38 | scfh/sf |

**Table 5.2:** Stage 1 and Stage 2 $H_2$ and CO separation from Phase 2 testing

| **Phase 2 $H_2$ and CO separation:** | **Stage 1** | **Stage 2** | **Units** |
|---|---|---|---|
| Test Gas $H_2$ input: | 50% | 89% | % |
| Test Gas Temperature (Reject): | 58 | 41 | °C |
| Feed pressure: | 102 | 81 | psig |
| Feed Partial Pressure $H_2$: | 51 | 73 | psi |
| Permeate Pressure: | 5 | 3 | psig |
| Permeate side gas composition (%): | 89% | 99%♠ | % |
| Permeate Partial Pressure $H_2$: | 5 | 3 | psi |
| $H_2$ Partial Pressure Diff: | 46 | 69 | psi |
| Membrane surface area: | 0.312 | 0.148 | $m^2$ |
| Total gas flow to membrane (lpm): | 8.55 | 3.38 | lpm |
| Total $H_2$ to membrane: | 4 | 3 | lpm |
| Permeate gas flow: | 4.06 | 2.86 | lpm |
| Recovery rate: | 85% | 93% | % |
| Permeance: | 0.22 | 0.24 | $m^3/m^2/hr/bar$ |
| Flux*: | 0.99 | 1.08 | scfh/sf |

* Flux corrected to 20 psi hydrogen partial pressure differential. No correction has been made for temperature, which is supposed to be at 400°C for DOE target flux rate.

♠ TCD was spanned with 100% $H_2$ during this test period and read 99%. The measured permeate side hydrogen content is as close to 100% Hydrogen as our instrumentation could measure.

Membrane performance particularly on the stage 1 modules was better when using hydrogen than when using helium.

## 6.0 Hydrogen production from Plasma Converted Gas

### *6.1 Objectives:*

6.1.1 To characterize StarCell operation using Plasma Converted Gas generated from a municipal solid waste surrogate

6.1.2 Compare StarCell System performance on Plasma Converter synthesis gas with laboratory test data and previous results obtained using bottled gases.

6.1.3 Determine if StarCell membrane modules are affected by low level contaminants in the synthesis gas.

## 6.2 Test Description:

### 6.2.1 Test Summary:

During this test, Plasma Converter Synthesis Gas was generated by the Plasma Converter System and will then be run through the StarCell Hydrogen Purification System. These systems were run concurrently. Results of the test was compared with previous data to evaluate membrane module performance using actual synthesis gas

### 6.2.2 Data and Analysis:

Data obtained from the Plasma Converter System was primarily gas composition data. System operating conditions was the same as during the independent lab gas analysis detailed in the Phase 1 test report. Data obtained from the StarCell system will include gas flows, gas temperatures, gas pressures, operation times, parameter changes, and observations of the system operation. Internal analysis was performed on the gas stream to determine hydrogen content after Stage 1 and after Stage 2.

### 6.2.3 External Testing:

Gas mixtures used for instrument calibration are analyzed and certified by third party laboratories. No additional third party analysis is required.

## *6.3 Synthesis gas generation results and discussion:*

Performance of the plasma converter was almost exactly the same as it was during Phase 1 testing. During Phase 1 it was noted that Startech CO data read 7 – 9 % below the laboratory results while all other measured gas compositions were within a percentage point. Figure 6.1 and Table 6.1 show raw average gas composition data from 8 laboratory samples (Lab Phase 1), 3 detailed gas runs from Phase 1 during which the lab samples were pulled (Log Phase 1), and 5 Phase 2 data log averages during which the Plasma Converted Gas was run through the StarCell System (Log Phase 2). The nitrogen content for the Startech gas compositions is a calculated value done with the assumption that the gas composition accounts for 100% of the Plasma converted gas.

**Figure 6.1:** Average Raw Gas Compositions for Phase 1 and Phase 2 testing

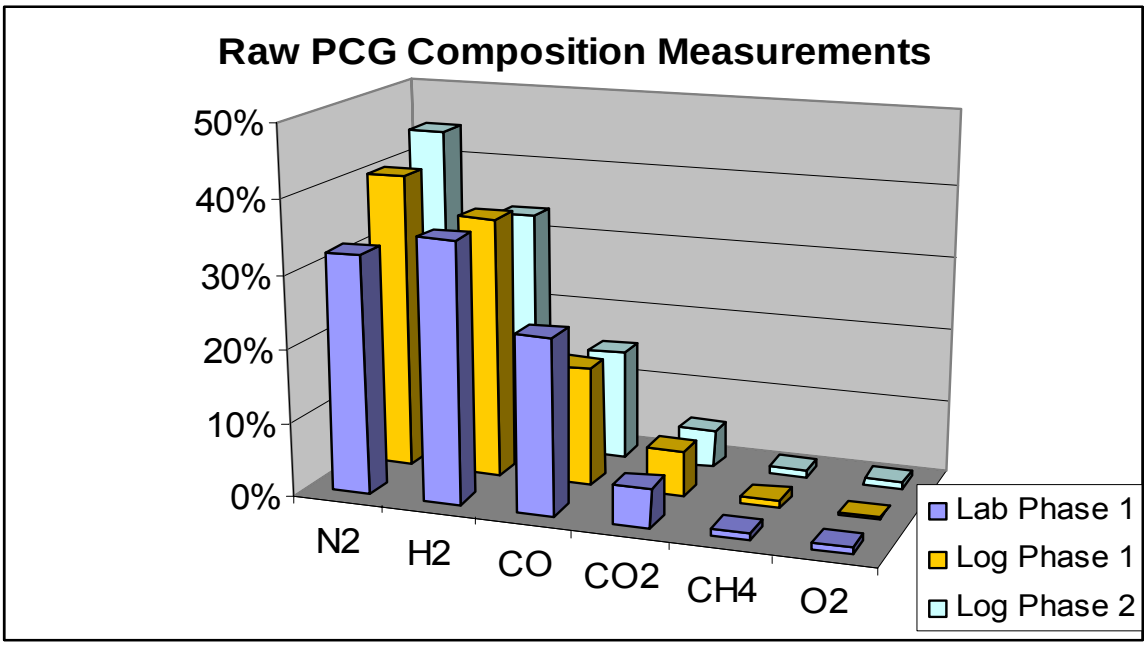



**Table 6.1:** Average Raw Gas Compositions for Phase 1 and Phase 2 Testing

| | $N_2$ | $H_2$ | CO | CO2 | $CH_4$ | $O_2$ |
|---|---|---|---|---|---|---|
| **Lab Phase 1** | 32.6% | 35.6% | 24.0% | 5.3% | 1.0% | 0.8% |
| **Log Phase 1** | 40.6% | 35.6% | 16.3% | 6.2% | 1.0% | 0.2% |
| **Log Phase 2** | 44.5% | 33.5% | 15.1% | 5.1% | 1.1% | 0.7% |

The gas composition measured by the laboratory during Phase 1 testing is also consistent with thermodynamic and chemical models that predict that the hydrogen to CO ratio should be 1.3 – 1.5. The lab results indicate hydrogen to CO ratio of about 1.5. The Startech Phase 1 and Phase 2 gas composition results indicate a ratio of hydrogen to CO of about 2.2. Table 6.2 and Figure 6.2 show the average lab results as received, and Startech gas composition results with the CO value calculated to be proportional to the difference in the Phase 1 Lab results and the Phase 1 logged results.

**Figure 6.2:** CO Corrected Gas Compositions for Phase 1 and Phase 2 testing

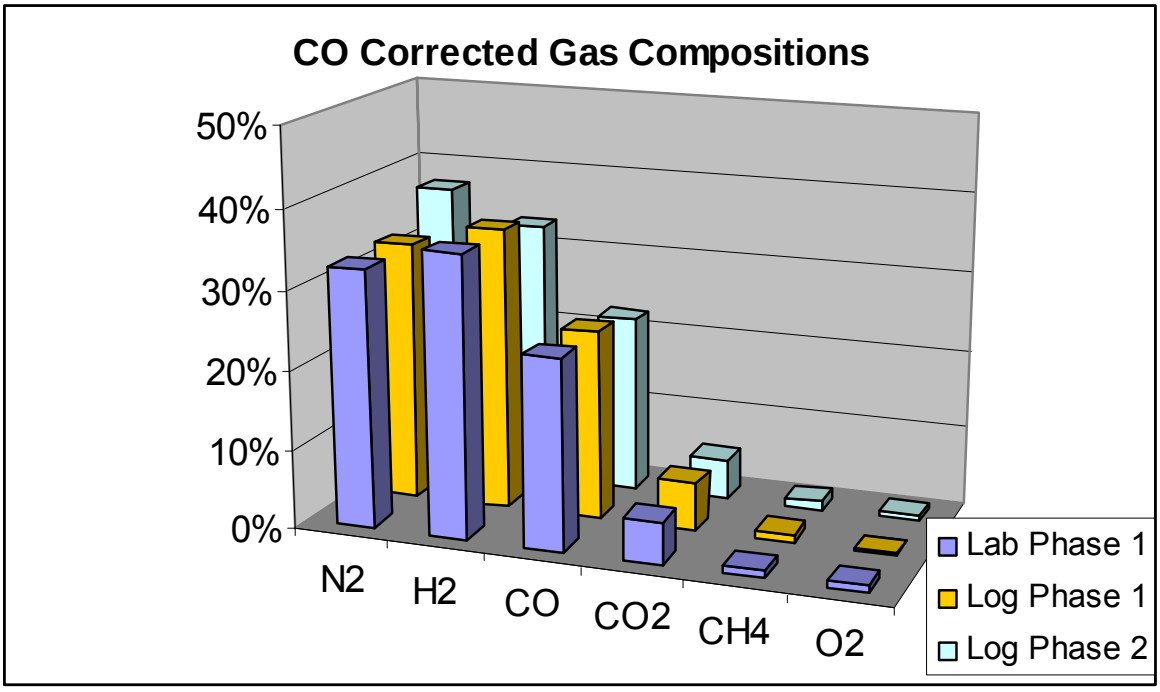



**Table 6.2:** CO Corrected Gas Compositions for Phase 1 and Phase 2 Testing

| | $N_2$ | $H_2$ | CO | CO2 | $CH_4$ | $O_2$ |
|---|---|---|---|---|---|---|
| **Lab Phase 1** | 32.6% | 35.6% | 24.0% | 5.3% | 1.0% | 0.8% |
| **Log Phase 1** | 32.9% | 35.6% | 24.0% | 6.2% | 1.0% | 0.2% |
| **Log Phase 2** | 37.3% | 33.5% | 22.3% | 5.1% | 1.1% | 0.7% |

The hydrogen composition of the Phase 2 gas was about 2% lower than it was for Phase 1, but was close enough where any differences in the membrane performance during hydrogen purification would be negligible. The gas composition of Log Phase 2 relative to Log Phase 1 indicates that there was likely some air leakage into the gas polishing train downstream of the Plasma Converter Vessel.

Commercial scale Plasma Converted Gas would look differently from the gas composition shown in Figure 6.2. Nitrogen dilution in the PCG generated and used during this series of tests would be reduced drastically for applications where PCG use was important. Changes required to reduce Nitrogen content in the PCG were not within the scope of this testing. Nitrogen could be mostly removed from the Plasma Converted Gas by eliminating air leakage through the feed system and using either recycled PCG or Membrane Tail Gas as the plasma medium. Figure 6.3 and Table 6.3 show PCG gas compositions adjusted from Phase 1 and Phase 2 data if the total nitrogen content were limited to 5%.

**Figure 6.3:** $N_2$ Limited Gas Composition for Phase 1 and Phase 2 testing

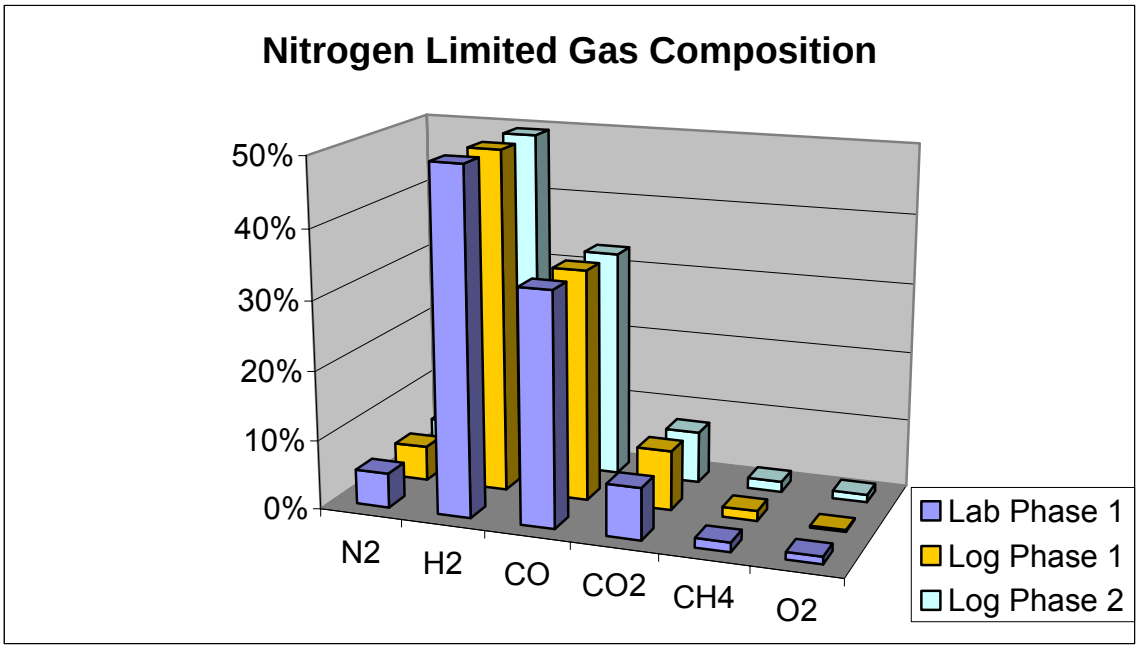



**Table 6.3:** $N_2$ limited Gas Composition for Phase 1 and Phase 2 testing

| | $N_2$ | $H_2$ | CO | $CO_2$ | $CH_4$ | $O_2$ |
|---|---|---|---|---|---|---|
| **Lab Phase 1** | 5.0% | 49.6% | 33.5% | 7.4% | 1.4% | 1.1% |
| **Log Phase 1** | 5.0% | 49.4% | 33.3% | 8.6% | 1.4% | 0.3% |
| **Log Phase 2** | 5.0% | 49.5% | 33.0% | 7.5% | 1.6% | 1.1% |

The results of the Nitrogen Limited data show that the gas composition generated strictly from the Municipal Solid waste being processed in the Plasma Converter is an excellent source of hydrogen and closely resembles the hydrogen content of the bottled mixed gases used in the Startech testing.

### *6.4 Hydrogen Purification from Plasma Converted Gas:*

Hydrogen purification from Plasma Converted Gas (PCG) was again performed under the same conditions as Phase 2 bottled gas testing and Phase 1 mixed gas testing last year. Sample results from Phase 2 PCG hydrogen separation are shown in Tables 6.6 and 6.7. Results from last years testing of the same type are shown in Tables 6.4 and 6.5.

**Table 6.4:** Phase 1, Stage 1 StarCell Separation Results

| | 11/30/05 | 12/1/05 | 1/12/06 | Units |
|---|---|---|---|---|
| Test Gas $H_2$ input: | 35% | 35% | 35% | % |
| Test Gas Temp. (Reject): | 45 | 48 | 33.5 | °C |
| Feed pressure: | 102 | 100 | 101 | psig |
| Feed Partial Pressure $H_2$: | 35.7 | 35 | 35.4 | psi |
| Permeate Pressure: | 7.5 | 8.6 | 8.0 | psig |
| Permeate side gas comp.: | 65% | 63% | 59% | % |
| Permeate Partial Pres. $H_2$: | 4.875 | 5.4 | 4.72 | psi |
| $H_2$ Partial Pressure Diff: | 30.825 | 29.6 | 30.63 | psi |
| Membrane surface area: | 0.304 | 0.304 | 0.304 | $m^2$ |
| Total flow to membrane: | 4.8 | 4.8 | 2.5 | lpm |
| Total $H_2$ to membrane: | 1.68 | 1.68 | 0.88 | lpm |
| Permeate gas flow: | 1.5 | 1.5 | 1.27 | lpm |
| Recovery rate: | 58% | 56% | 86% | % |
| Permeance: | 0.139 | 0.145 | 0.119 | $m^3/m^2/hr/bar$ |
| Flux: | 0.63 | 0.66 | 0.54 | scfh/sf |

**Table 6.5:** Phase 1, Stage 2 Hydrogen Purification of PCG

| | | Stage 2 | Stage 2 | Units |
|---|---|---|---|---|
| Test Gas $H_2$ input: | | 52% | 52% | % |
| Test Gas Temp. (Reject): | | 37.3 | 38 | °C |
| Feed pressure: | | 84.2 | 85.2 | psig |
| Feed Partial Pressure $H_2$: | | 43.8 | 44.3 | psi |
| Permeate Pressure: | | 15.4 | 12.8 | psig |
| Permeate side gas comp.: | | 79% | 77% | % |
| Permeate Partial Pres. $H_2$: | | 12.2 | 9.9 | psi |
| $H_2$ Partial Pressure Diff: | | 31.6 | 34.4 | psi |
| Membrane surface area: | | 0.156 | 0.156 | $m^2$ |
| Total flow to membrane: | | 1.0 | 0.4 | lpm |
| Total $H_2$ to membrane: | | 0.52 | 0.21 | lpm |
| Permeate gas flow: | | 0.23 | 0.18 | lpm |
| Recovery rate: | | 35% | 65% | % |
| Permeance: | | 0.041 | 0.029 | $m^3/m^2/hr/bar$ |
| Flux: | | 0.18 | 0.13 | scfh/sf |

**Table 6.6:** Phase 2, Stage 1 Hydrogen Separation from PCG Results

| | 5/18/07 | 6/6/07 | 6/7/07 | 6/8/07 | Units |
|---|---|---|---|---|---|
| Test Gas $H_2$ input: | 35% | 33.6% | 35.2% | 31.5% | % |
| Test Gas Temp. (Reject): | 67.211 | 62.7 | 54.2 | 54.8 | °C |
| Feed Pressure: | 119 | 124 | 130 | 130 | psig |
| Feed Partial Pressure $H_2$: | 41.055 | 41.5 | 45.8 | 40.9 | psi |
| Permeate Pressure: | 2.6667 | 3.5714 | 4.5 | 3 | psig |
| Permeate Gas Comp.: | 79% | 72% | 73% | 76% | % |
| Permeate Partial Pres. $H_2$: | 2.1022 | 2.6 | 3.3 | 2.3 | psi |
| $H_2$ Partial Pressure Diff: | 38.953 | 38.9 | 42.5 | 38.6 | psi |
| Membrane surface area: | 0.312 | 0.312 | 0.312 | 0.312 | m2 |
| Total Flow to Membrane: | 9.2 | 10.1 | 10.5 | 11.3 | lpm |
| Total $H_2$ to Membrane: | 3.1771 | 3.4 | 3.7 | 3.5 | lpm |
| Permeate Gas Flow: | 2.9789 | 2.6 | 2.9 | 3.0 | lpm |
| Recovery Rate: | 74% | 56% | 57% | 65% | % |
| Permeance: | 0.168 | 0.136 | 0.137 | 0.166 | $m^3/m^2/hr/bar$ |
| Flux: | 0.76 | 0.615 | 0.622 | 0.751 | scfh/sf |

**Table 6.7:** Phase 2, Stage 2 Hydrogen Separation from PCG Results

| | 5/18/07 | 6/7/07 | 6/8/07 | Units |
|---|---|---|---|---|
| Test Gas $H_2$ Input: | 79% | 73.2% | 76.3% | % |
| Test Gas Temp. (Reject): | 40.76 | 61.6 | 46.2 | °C |
| Feed Pressure: | 49.2 | 85 | 96 | psig |
| Feed Partial Pressure $H_2$: | 38.786 | 62.4 | 73.2 | psi |
| Permeate Pressure: | 1.5 | 5.75 | 0.36 | psig |
| Permeate Gas Comp.: | 98% | 94% | 94% | % |
| Permeate Partial Pres. $H_2$: | 1.464 | 5.4 | 0.3 | psi |
| $H_2$ Partial Pressure Diff: | 37.322 | 57.0 | 72.9 | psi |
| Membrane Surface Area: | 0.148 | 0.148 | 0.148 | m2 |
| Total Flow to Membrane: | 2.2235 | 3.1 | 1.5 | lpm |
| Total $H_2$ to Membrane: | 1.7529 | 2.3 | 1.2 | lpm |
| Permeate Gas Flow: | 1.4475 | 1.9 | 1.1 | lpm |
| Recovery Rate: | 81% | 79% | 91% | % |
| Permeance: | 0.223 | 0.184 | 0.085 | $m^3/m^2/hr/bar$ |
| Flux: | 1.01 | 0.833 | 0.383 | scfh/sf |

The results from the Phase 2 testing again showed an improvement over the Phase 1 testing. The stage 1 flux and permeance calculations during Phase 2 testing were similar to stage 1 flux and permeance results from the Phase 1

test. However, the flow from the Stage 1 permeate during Phase 2 testing was about twice what it was during Phase 1 testing, and the purity of the recovered hydrogen was higher, (72 – 76% vs. 59 - 65%).

Stage 1 operation during the PCG test was optimized for flow of permeate to the stage 2 membranes so there would be enough pressurized permeate to test stage 2. For this reason, the recovery rate was not optimized. In comparing Phase 1 and Phase 2 test results, it is important to note that the Stage 1 permeate flowmeter was changed out prior to Phase 2 testing for a flowmeter that was calibrated for 100% hydrogen. This change affected the results by giving an unquantified lower stage 1 permeate flow reading for non-hydrogen gas in the permeate. Therefore the recovery rates calculated and shown for Phase 2 stage 1 shown in Table 6.5 above is likely lower than the actual recovery rate. This had a larger effect on the PCG testing than other tests as the Hydrogen in the PCG permeate was lower than for the other test gases. Also, any leakage that had developed over the course of the testing in the o-rings or potting material would have a detrimental effect on the results of the testing. Potential leakage effects and membrane degradation that may have affected these results are discussed in Section 7.3.

The biggest difference between Phase 1 and Phase 2 testing can be seen when comparing the Stage 2 hydrogen results. Once again, flux and permeance for the Phase 2 stage 2 membranes were 3 – 5 times better than for Phase 1 stage 2 membranes. All other conditions between the two tests were relatively constant. The two primary reasons for the better performance are improved membranes. The improved permeate gas from stage 1 also likely contributed to the better performance, but this was again due to improved stage 1 membranes as the PCG going to the system was of constant composition and quality.

The data shown represents two test conditions. The controlling variables in our system were the reject flow rate and the pressure. Reject flow was restricted more during operations on 6/8/07 than it was on 6/7/07 resulting in higher recovery rates and a lower flow through the membrane. Pressure was left at the maximum based on the availability of stage 1 permeate. Analysis of the datasheet also reflects a reduction on purity from ~ 94% to ~ 90% (Not reflected in the table above due to averaging) which is expected. The difference in operating conditions had a significant effect on the calculated Flux and permeance.

**Table 6.8*:*** Phase 2, Stage 2 Hydrogen Separation from PCG Result: Before and After a Reject Slow Adjustment, 6/8/07

| | Before | After | After | Units |
|---|---|---|---|---|
| Test Gas $H_2$ Input: | 76.3% | 76.3% | 76.3% | % |
| Test Gas Temp. (Reject): | 45.4 | 48.0 | 48.3 | °C |
| Feed Pressure: | 95 | 96 | 96 | psig |
| Feed Partial Pressure $H_2$: | 72.5 | 73.2 | 73.2 | psi |
| Permeate Pressure: | 0 | 1 | 1 | psig |
| Permeate Gas Comp.: | 92% | 92% | 92% | % |
| Permeate Partial Pres. $H_2$: | 0.0 | 0.9 | 0.9 | psi |
| $H_2$ Partial Pressure Diff: | 72.5 | 72.3 | 72.3 | psi |
| Membrane Surface Area: | 0.148 | 0.148 | 0.148 | m2 |
| Total Flow to Membrane: | 1.1 | 2.2 | 1.9 | lpm |
| Total $H_2$ to Membrane: | 0.9 | 1.7 | 1.5 | lpm |
| Permeate Gas Flow: | 0.8 | 1.6 | 1.4 | lpm |
| Recovery Rate: | 89% | 90% | 88% | % |
| Permeance: | 0.062 | 0.121 | 0.104 | $m^3/m^2/hr/bar$ |
| Flux: | 0.280 | 0.548 | 0.470 | scfh/sf |

Note: Permeate hydrogen composition set to a constant concentration to account for an analyzer calibration that was done in the midst of these measurements. The hydrogen content shown above is the post-calibrated result and as such is most representative of actual conditions.

## 7.0 Test Analysis and Discussion

### *7.1 Temperature:*

Changes made in temperature capability may have also had a positive effect on the performance of the membranes. The actual temperature of the gas passing through the membranes proved extremely difficult to measure accurately.

Despite the data showing that the reject temperature was approximately the same for Phase 2 testing as it was in Phase 1 testing, the temperature in Phase 2 testing was definitely higher. Spot measurements of the tube temperature leading directly into the membrane module during shakedown and mixed gas testing showed an entry temperature of ~ 120° C. After the initial May PCG testing, the tubes leading from the Induction heaters to the membranes for both stage 1 and stage 2 was also heat traced inside the insulation and a temporary thermocouple was affixed to the outside of the tube leading directly into the membrane module. These temperatures measured approximately 400°F – 450°F (204 - 232° C) while the reject

temperatures of the module tail gas remained 50°C – 60°C. The reject temperatures were clearly related to reject flow and increased rapidly with increases in reject flow rate through the system. Drastic increases in membrane performance due to increased gas temperatures through the membrane were not observed. Such differences would have been observed between the May 18, 2007 data and the June 6, 2007 PCG data at which point the heat tracing was added to the module inlet tubing.

### *7.2 Pressure:*

While flux and permeance calculations both adjusted for pressure differences, some of the data indicated that there might be more than a linear dependence of performance on pressure. Most notably, the data collected during shakedown testing (See Table 4.1) indicated that there could be a significant improvement to membrane performance with an increase in gas feed pressure. The observed increase in membrane performance beyond linear improvement was not observed in later data and was attributed to other changes in the operating conditions such as an increase in reject flow rate.

### *7.3 Membrane degradation:*

A battery of tests was performed on the membranes at the end of all the testing to evaluate degradation of the membranes after extended exposure to test conditions. The first round of testing utilized a calibrated blend of mixed Hydrogen and Carbon Monoxide as described in Section 5 of this report. The second round of testing utilized pure Hydrogen and Nitrogen to evaluate the selectivity and permeance of the membranes for comparison with earlier data

**Table 7.1:** Phase 2, Membrane Performance Comparison Data for Mixed Gas at the Start and End of Testing.

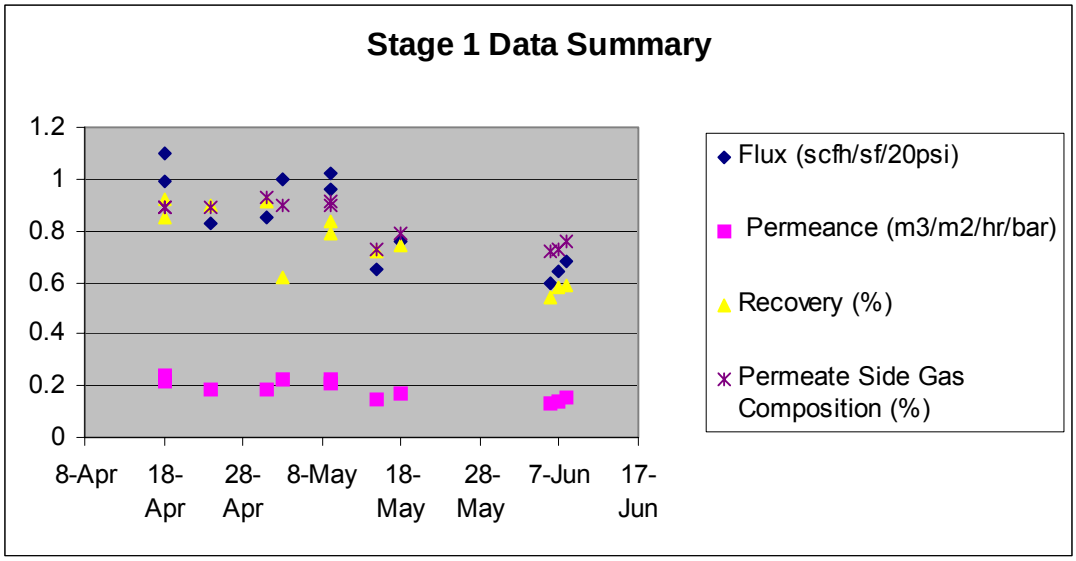
| | Stage 1 | | Stage 2 | | Units |
|---|---|---|---|---|---|
| | 4/24/07 | 7/24/07 | 4/24/07 | 7/24/07 | Date |
| Test Gas $H_2$ Input: | 50% | 50% | 89% | 50% | % |
| Test Gas Temp. (Reject): | 50.922 | 37.6 | 35.15 | 64.3 | °C |
| Feed Pressure: | 111.56 | 103 | 102 | 102 | psig |
| Feed Partial Pressure $H_2$: | 55.778 | 51.429 | 90.78 | 51 | psi |
| Permeate Pressure: | 6 | 1.1429 | 3 | 0 | psig |
| Permeate Gas Comp.: | 89% | 66% | 97% | 89% | % |
| Permeate Partial Pres. $H_2$: | 5.34 | 0.7527 | 2.91 | 0 | psi |
| $H_2$ Partial Pressure Diff: | 50.438 | 50.676 | 87.87 | 51 | psi |
| Membrane Surface Area: | 0.312 | 0.312 | 0.148 | 0.148 | $m^2$ |
| Total Flow to Membrane: | 7.3878 | 4.24 | 2.8667 | 2.84 | lpm |
| Total $H_2$ to Membrane: | 3.6939 | 2.1189 | 2.5513 | 1.42 | lpm |
| Permeate Gas Flow: | 3.7189 | 2.05 | 2.5417 | 1.29 | lpm |
| Recovery Rate: | 90% | 64% | 97% | 81% | % |
| Permeance: | 0.183 | 0.074 | 0.165 | 0.133 | $m^3/m^2/hr/bar$ |
| Flux: | 0.83 | 0.34 | 0.75 | 0.60 | scfh/sf |

The data in Table 7.1 shows that there was a greater degree of degradation on the stage 1 membranes than on the stage 2 membranes, which indicates there was some kind of contamination that was filtered out of the gas at stage 1 and therefore did not contaminate stage 2 as much. The frequency and pattern of the data points (shown in Table 7.2 and Figure 7.1) suggests that this is a time related degradation rather than a gas volume or composition related event. The degradation was also seen across the mixed gas testing and the PCG testing. The flux and permeance of the PCG test was lower than that of the mixed gas tests, though this is likely due to the difference in Hydrogen content of the feed gas. This observation is reinforced by the similarity in the May PCG data and the June PCG data. Stage 1 PCG separation data collected from June 6 - June 8 actually showed an increase in membrane flux and permeance that is an indication that it is probably not a PCG contaminant issue. If the degradation were due to a PCG gas contaminant, one would expect to see an incremental drop in membrane performance with each day's operation using PCG as the feedstock. This was not the case.

**Table 7.2**: Stage 1 Data Summary

| Date | Flux (scfh/sf/20psi) | Permeance ($m^3/m^2/hr/bar$) | Recovery (%) | Total $H_2$ to Membrane (lpm) | Permeate Side Gas Composition (%) |
|---|---|---|---|---|---|
| 18-Apr | 0.99 | 0.22 | 85% | 4 | 89% |
| 18-Apr | 1.1 | 0.242 | 92% | 4.4565 | 89% |
| 24-Apr | 0.83 | 0.183 | 90% | 3.6939 | 89% |
| 1-May | 0.85 | 0.187 | 91% | 3.5336 | 93% |
| 3-May | 1 | 0.221 | 62% | 6.4475 | 90% |
| 9-May | 0.96 | 0.211 | 79% | 4.2442 | 91% |
| 9-May | 1.02 | 0.225 | 84% | 6.8233 | 90% |
| 15-May | 0.65 | 0.145 | 72% | 2.6947 | 73% |
| 18-May | 0.76 | 0.168 | 74% | 3.1771 | 79% |
| 6-Jun | 0.6 | 0.132 | 54% | 3.486 | 72% |
| 7-Jun | 0.64 | 0.14 | 58% | 3.6289 | 73% |
| 8-Jun | 0.68 | 0.151 | 59% | 3.8819 | 76% |

**Figure 7.1:** Stage 1 Data Summary




Based on the data, it is believed that there are likely 2 causes of the membrane degradation observed. The first is a slow degradation that was seen across all of the testing. It is not known whether this is a contaminant related issue or just the normal progression of the membrane performance. It has been stated by the membrane supplier, Media and Process Technologies (M&PT), that the membranes can be regenerated by "baking them out" and as this such may not be true membrane degradation. The second cause of the membrane degradation was observed late in the testing essentially between the June tests and the last set of membrane evaluation tests. It is believed that a leak developed in

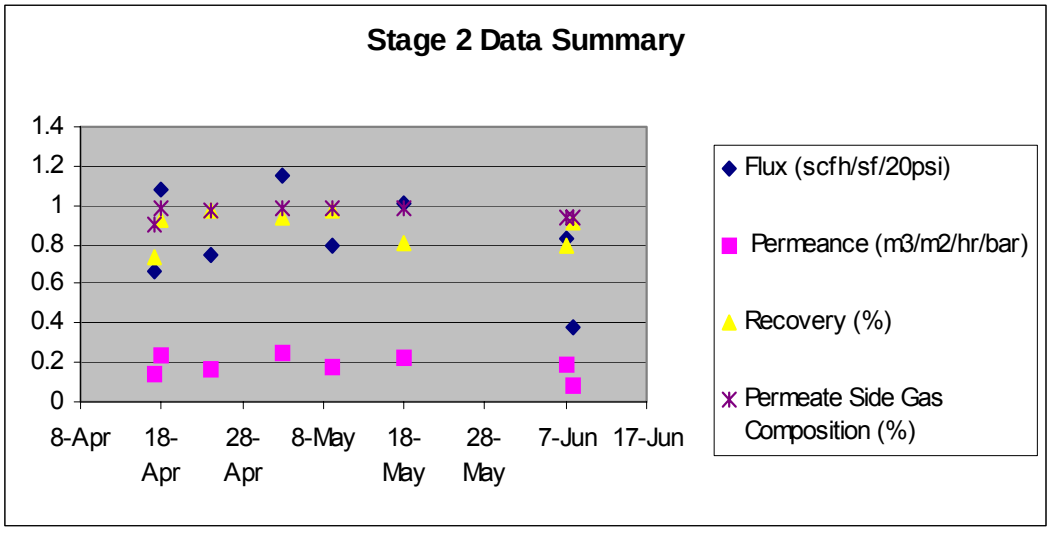
the Stage 1 modules immediately prior to the June PCG tests. The leak was likely due to an o-ring failure caused by overheating the o-ring in the membrane module with the heat tape. Organics given off by the degradation of the o-ring or another component of the system could have been the cause of the degradation of membrane performance. This is the reason the recovery rates for the June PCG tests were so much lower than for the previous tests including the May PCG tests. There was also moisture observed in some of the sample lines going to the Hydrogen analyzer in the July testing. It is not known whether heat cycling moisture on the membranes could have contributed to degradation.

**Table 7.2**: Stage 2 Data Summary

| Date | Flux (scfh/sf/20psi) | Permeance ($m^3/m^2/hr/bar$) | Recovery (%) | Total $H_2$ to Membrane (lpm) | Permeate Side Gas Composition (%) |
|---|---|---|---|---|---|
| 17-Apr | 0.67 | 0.147 | 74% | 2.47 (He) | 90% |
| 18-Apr | 1.08 | 0.24 | 93% | 3 | 99% |
| 24-Apr | 0.75 | 0.165 | 97% | 2.5513 | 97% |
| 3-May | 1.15 | 0.254 | 94% | 4.0004 | 99% |
| 9-May | 0.79 | 0.174 | 97% | 2.8211 | 98% |
| 18-May | 1.01 | 0.223 | 81% | 1.7529 | 98% |
| 7-Jun | 0.83 | 0.184 | 79% | 2.2601 | 94% |
| 8-Jun | 0.38 | 0.085 | 91% | 1.1514 | 94% |

**Note:** Please see Section 6 for discussion on the difference between 7 Jun and 8 Jun data for flux and permeance for the stage 2 membrane.

**Figure 7.2:** Stage 2 Data Summary



### *7.4 Progress toward DOE targets*

**Startech Membrane Module Data:** Data obtained while purifying a 50% $H_2$, 50% CO Gas Blend, Co-current flow, no sweep gas

| Performance Criteria | Units | 2003 Status | 2005 Target | 2005 Dec. | 2007 June | 2010 Target |
|---|---|---|---|---|---|---|
| Flux Rate | scfh/ft2 | 100 | 100 | 0.641 | 1.08 | 200 |
| Membrane Material and All Module Costs | $/ft2 of Membrane | 450-600 | 400 | TBD | 65 | 200 |
| Durability | hr | <8,760 | 8,760 | TBD[2] | TBD | 26,280 |
| ΔP Operating Capability | psi | 100 | 200 | TBD[3] | >150[3] | 400 |
| Hydrogen Recovery | % of total gas | 60 | >70 | 80% | 90%[5]<br>94% | >80 |
| Hydrogen Quality | % of total (dry) gas | >90 | 95 | 96%[4] | 90%[5]<br>>99% | 99.5 |

1 Flux was determined at 20 psi hydrogen partial pressure differential with a minimum permeate side total pressure of 1.2 psi, and 60°C. Flux is expected to increase logarithmically with increased operating temperature.

2 The durability of the membranes has not been determined in terms of total hours. The membranes can be regenerated once poisoned using a high temperature gas flush. The period between flush cycles will vary based on contaminant concentrations, the type of contaminant, and operating temperature.

3 Delta P was tested between 100 and 150 psi. The membrane modules were outfitted with 150 lb ANSI flanges. The membranes themselves were not tested to failure to determine the operating capability.

4 Hydrogen quality is expected to increase with better selectivity which will be obtained at higher temperatures and will also be improved with higher initial concentration of hydrogen. Hydrogen purity of 98% to >99% can likely be obtained with current modules with a hydrogen input purity of 80%. The composition of the non-hydrogen balance of the gas will also have a significant effect on the membrane performance.

5 Top numbers in both cases are single pass results from a 50% mixture of hydrogen and carbon monoxide. 90% recovery and 90% purity were typical numbers. The bottom number in both cases was typical of second pass data using 80% - 90% hydrogen input from a stage 1 permeate tank.

### *7.5 List of Accomplishments:*

- Generated a hydrogen-rich synthesis gas from municipal solid waste (MSW) surrogate waste material with a net hydrogen concentration of 50% by volume. Rate of gas generation was ~150 scfm.
- Tested multiple modules of membranes on both laboratory gases and on synthesis gas generated from the MSW surrogate material.
- Tested multiple generations of Modules and verified advancements of pilot scale membrane modules.
- Characterized membrane operation under various conditions
- Purified CO and $H_2$ blend gas from 50% $H_2$ to >99% $H_2$ (as pure as could be measured). Synthesis gas was purified from 35% $H_2$ to ~94% $H_2$.
- Synthesis gas produced from MSW was shown to be low in contaminants and suitable for many subsequent processes including direct hydrogen purification through carbon coated ceramic membranes.
- Exceeded DOE 2010 targets for Hydrogen Recovery and Purity from pilot scale membrane modules. Demonstrated significant improvement towards other targets.

## *8.0 Conclusion and Discussion*

The research done in this project showed advancements in many technical areas in support of large scale hydrogen production. Hydrogen rich synthesis gas was produced from waste material on a commercial scale. This is significant as municipal solid waste was heretofore not even considered as a potential large scale source of hydrogen. Furthermore, the Plasma Converter System has the potential for application not only to waste materials, but also to abundant biomass feedstocks that are not amenable to gasification by other methods for various reasons. The results of this testing also showed that the gas produced in a Plasma Converter System from municipal solid waste was very clean with ~50% hydrogen content before water gas shift. The gas produced was suitable for many applications including subsequent purification through carbon molecular sieve membranes.

The membrane data obtained during this testing was also very significant. The membranes used were actual commercial scale membrane bundles (referred to as Modules) in this testing, so all of the test results reported are essentially pilot scale. Also, actual gasification gas was used from a non-fossil source as the feedstock for these membranes rather that clean natural gas. No sweep gases or other process aides were used that would improve performance statistics while decreasing the practical use of the gas. Even under these conditions, the StarCell system demonstrated gas purification from a 50% concentration to 100% purity (as close as could be measured) in two passes and showed hydrogen recovery rates in excess of 90% from a 50% gas mixture. The

effectiveness of regenerating the membranes to maintain the performance needs to be determined, and they do seem susceptible to contamination, but this might be addressed using an inexpensive prefilter. With regard to pressure and temperature, the membranes themselves seem flexible and robust, but the Module housings and sealing design need to be improved if the membranes are to operate outside of the range tested in this effort.

# Appendix A: StarCell Data Sheets

**Date: April, 12 2007**
**Stage 1**
**Membrane Feed: 50% He/$N_2$**

| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate |
|---|---|---|---|---|---|---|---|---|---|---|
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | % H2 | |
| 1:08 | 95 | 170.5 | 25.3 | 95 | 5.9 | | 7 | 5.88 | 21.5 | 76 |
| 1:15 | 94 | 173.5 | 26.6 | 94 | 5.8 | | 8 | 5.8 | 34 | 78 |
| 1:20 | 95 | 182.4 | 28.5 | 95 | 6.3 | | 9 | 5.76 | 28 | 78 |
| 1:25 | 94 | 182.4 | 29.8 | 94 | 6.36 | | 8 | 5.8 | 27 | 78 |
| 1:30 | 95 | 181.4 | 30.8 | 94 | 6.38 | | 10 | 5.6 | 27 | 78 |
| 1:35 | 94 | 182 | 32.5 | 94 | 6.32 | | 5 | 6.32 | 25 | 79 |
| 1:40 | 94 | 185 | 34.1 | 94 | 6.32 | | 7 | 6.07 | 26 | 78.5 |
| 1:45 | 94 | 187.5 | 35.2 | 94 | 6.38 | | 8 | 5.89 | 26 | 78.5 |
| 1:50 | 95 | 186.5 | 36.1 | 95 | 6.34 | 70 | 10 | 5.75 | 26.5 | 78 |
| 1:55 | 95 | 189.8 | 37.1 | 95 | 6.36 | 70 | 5 | 6.38 | 25 | 79 |
| 2:00 | 95 | 188.7 | 38.1 | 95 | 6.38 | 70 | 6 | 6.19 | 26 | 79 |
| 2:05 | 94 | 190 | 39 | 95 | 6.4 | 70 | 8 | 5.96 | 26 | 78.5 |
| 2:10 | 95 | 191.4 | 39.7 | 95 | 6.35 | 70 | 10 | 5.77 | 26.5 | 78.5 |
| 2:15 | 94 | 192 | 40.5 | 94 | 6.33 | 81 | 5 | 6.38 | 25 | 79 |
| 2:20 | 95 | 192.5 | 41.2 | 95 | 6.44 | 80 | 6 | 6.21 | 26 | 79 |
| 2:25 | 95 | 195.5 | 41.8 | 95 | 6.43 | 80 | 8 | 6.03 | | |
| 2:30 | 95 | 209 | 42.8 | 95 | 10.19 | 80 | 10 | 6.18 | 30.5 | 79.5 |
| 2:35 | 95 | 211.8 | 42.8 | 95 | 10.12 | 91 | 5 | 6.87 | 30 | 80 |
| 2:40 | 95 | 213.8 | 43.3 | 95 | 10.16 | 91 | 6 | 6.67 | 30 | 80 |
| 2:45 | 95 | 216 | 43.8 | 95 | 10.2 | 91 | 8 | 6.41 | 30.5 | 80 |
| 2:50 | 95 | 216.2 | 44 | 95 | 10.1 | 91 | 10 | 6.9 | 30.5 | 80 |
| 2:55 | 95 | 218 | 44.8 | 95 | 10.2 | 102 | 6 | 6.76 | 30 | 80 |
| 3:00 | 96 | 217.8 | 45 | 96 | 9.9 | 102 | 7 | 6.64 | 30.5 | 80 |
| 3:05 | 95 | 222.8 | 45.3 | 96 | 10.26 | | 8 | 6.46 | 30.5 | 80 |
| 3:10 | 96 | 225.6 | 46.7 | 96 | 10.27 | 113 | 3 | 7 | 30 | 80 |
| 3:15 | 96 | 220 | 46.3 | 96 | 10.24 | | 5 | 6.91 | 30 | 80 |

*Used 100% N2 and 100% H2 for zero and span gas (respectively) prior to testing

**Date: April, 13 2007**
**Stage 2**
**Membrane Feed: 50% He/$N_2$**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 | | | |
| 12:23 | | | | | | | | | 48.5 | | |
| 12:30 | | | | | | | | | 24 | 83.5 | |
| 12:35 | | | | | | | | | 19 | 82.5 | |
| 12:40 | | | | | | | | | 17 | 81 | |
| 12:50 | | | | | | | | | 19 | 80.5 | |
| 1:15 | | | | | | | | | 20 | 82 | |
| 1:25 | | | | | | | | | 21 | 82 | |
| 1:27 | VP PT709 to 80 | | | | | | | | | | |
| 1:30 | | | | | | | | | 19.5 | 84 | |
| 1:50 | | | | | | | | | 18 | 83 | |
| 2:00 | | | | | | | | | 18.5 | 83.5 | |
| 2:20 | | | | | | | | | 18 | 83 | |
| 2:38 | | | | | | | | | 18 | 83 | |
| 3:15 | Cal from tank = 47% | | | | | | | | | | |

*Ran compressed gas from stage 2 storage tank through stage 2 membrane. This gas was inadvertently diluted during warm up with nitrogen from the
* Used 100% N2 and 100% H2 for zero and span gas (respectively) prior to testing

**Date: April, 17 2007**
**Stage 1 (Operated from 1:27 pm - 2:20 pm)**
**Stage 2 (Operated from 3:10 pm - 2:20 pm)**
**Membrane Feed: 50% $He/N_2$**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Reject | Permeate |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | | | |
| 1:27 | | | | | | | | | 24.5 | 81 | | |
| 1:35 | | | | | | | | | 26 | | | |
| 1:53 | | | | | | | | | 26 | 80.5 | | |
| 2:00 | | | | | | | | | 25 | 81 | | |
| 2:10 | | | | | | | | | 26 | 80.5 | | |
| 2:20 | | | | | | | | | 26 | 81 | | |
| 3:10 | | | | | | | | | | | 47 | 89.5 |
| 3:20 | | | | | | | | | | | 46.5 | 90 |
| 3:40 | | | | | | | | | | | 48.5 | 90 |
| 3:55 | | | | | | | | | | | 49 | 90 |

**Date: April, 18 2007**
**Stage 1**
**Membrane Feed: 50% $H_2$/CO**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | |
| 10:38 | 99 | 205.5 | 58.9 | 99 | 4.69 | 43.2 | 5 | 4.2 | 26 | 91 |
| 10:57 | 104 | 211.4 | 57.5 | 105 | 4.33 | 52.1 | 4 | 4.3 | 24 | 90 |
| 11:14 | 105 | 213.9 | 53.6 | 105 | 4.39 | 52.4 | 5 | 4.23 | 24.5 | 90 |
| 11:32 | 105 | 220.1 | 53.2 | 105 | 4.07 | 55.5 | 7 | 4.02 | 24.5 | 89 |
| 11:46 | 105 | 219.2 | 51.5 | 105 | 3.86 | 55.3 | 7 | 4.01 | 23 | 89 |
| 12:02 | 105 | 221.6 | 51 | 105 | 3.7 | 55.6 | 8 | 3.9 | 23 | 88 |
| 12:13 | Bumped FIT 701 to 5.9-6.0 | | | | | | | | | |
| 12:14 | 105 | 228.4 | 55 | 105 | 5.79 | 56.6 | 7 | 4.37 | 28.5 | 89.75 |
| 12:45 | 106 | 234.7 | 59.4 | 106 | 4.96 | 58.3 | 4 | 4.34 | 26 | 89.5 |
| 1:57 | 107 | 241.1 | 59 | 107 | 4.17 | 59.1 | 5 | 4.11 | 24 | 88.5 |
| 2:15 | 107 | 240.9 | 59.1 | 107 | 4.14 | 59.1 | 7 | 3.97 | 24.5 | 88.5 |
| 2:30 | 107 | 240.8 | 59.9 | 107 | 4.17 | 59.4 | 8 | 3.96 | 25 | 88.5 |
| 2:47 | | | | | | | | | 24 | 89 |
| 3:09 | 108 | 242.4 | 60.1 | 108 | 4 | 59.6 | 7 | 3.99 | 24.5 | 88 |
| 4:15 | 108 | 244.2 | 61.2 | 108 | 3.92 | 59.7 | 7 | 10.28 | 23 | 91 |

**Date: April, 18 2007**
**Stage 2**
**Membrane Feed: 50% $H_2$/CO**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 | | | |
| 2:20 | Initial stage 2 gas composition 84% H2 | | | | | | | | | | |
| 2:33 | 104 | 204.5 | 45.6 | 104 | 0.5 | 71.8 | 0 | 3.49 | 30 | 95.5 | |
| 2:39 | Adjust stage 2 reject to 2.5 LPM: Target 50% H2 | | | | | | | | | | |
| 2:45 | 96 | 214.2 | 53.2 | 96 | 2.84 | 89.3 | 6 | 3.7 | 75 | 96.5 | |
| 2:51 | | | | | | | | | 76 | 96 | |
| 3:13 | 94 | 213 | 47.8 | 93 | 0.49 | 96.3 | 4 | 3.02 | 51.5 | 96 | |
| 3:24 | Recalibrate with Pure H2 reading 99% | | | | | | | | 36 | 98 | |
| 3:30 | | | | | | | | | 36 | 98.5 | |
| 3:39 | | | | | | | | | | 98.5 | |
| 4:15 | 94 | 220 | 37.9 | 74 | 0.39 | 102.9 | 2 | 2.62 | 34 | 99 | |

**Date: April, 24 2007**
**Stage 1 (Initiated flow simultaneously with stage 2)**
**Membrane Feed: 50% $H_2$/CO**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | |
| 10:08 | Check stage 1 reject after about 15 minutes of flow. =50% H2 (Have not allowed flow through permeate side) | | | | | | | | | |
| 10:52 | 111 | 178.5 | 49.6 | 111 | 6.05 | 51.2 | 7 | 4.07 | 33 | 91 |
| 11:37 | 111 | 192 | 48.2 | 111 | 3.82 | 57.8 | 7 | 3.75 | 33 | 91 |
| 11:41 | 111 | 192.7 | 48.8 | 111 | 3.61 | 58.4 | 3 | 3.97 | 25.5 | 91.5 |
| 12:32 | 111 | 204.1 | 51.2 | 111 | 3.82 | 59.4 | 5 | 3.81 | 24.5 | 92.5 |
| 12:36 | Calibration reading 50% H2 reads 53%, 100%>100%, adjust 100%, check with 50%, 50% reads 51.15 | | | | | | | | | |
| 12:44 | 112 | 206.8 | 51.6 | 112 | 3.81 | 58.6 | 8 | 3.71 | 25 | 87.5 |
| 1:00 | 112 | 209 | 51.1 | 112 | 2.96 | 58.3 | 5 | 3.61 | 19.5 | 86 |
| 1:32 | 112 | 214.7 | 51.6 | 112 | 3.02 | 58.5 | 5 | 3.59 | 19 | 87 |
| 1:33 | Span calibration = 51% + 100% | | | | | | | | | |
| 2:08 | 112 | 218.3 | 52.5 | 112 | 3.03 | 58.3 | 6 | 3.53 | 20 | 87 |
| 2:46 | 112 | 222.1 | 53.7 | 112 | 2.9 | | 8 | 3.43 | 19 | 87.5 |
| 3:18 | 76 | 216.5 | 50 | 76 | 2 | 55.5 | 6 | 2.05 | 23 | 87 |
| 4:21 | 34 | 207.2 | 41 | 34 | 0.99 | 43.8 | 7 | 0.5 | | |

**Date: April, 24 2007**
**Stage 2 (Initiated flow simultaneously with stage 1)**
**Membrane Feed: 50% $H_2$/CO**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 | | |
| 9:30 | Calibrate H2 analyzer with pure H2 and 50% H2/Co balance | | | | | | | | | |
| 9:35 | (Check data logger for activation time) Measured H2 content of stage 2 holding tank, h2 content=87.5-decided not to drain stage 2 tank | | | | | | | | | |
| 10:08 | Check, see stage 1 sheet | | | | | | | | | |
| 12:46 | Start stage 2 flow. Tank reading 87.5% H2 | | | | | | | | | |
| 12:50 | 105 | 187 | 40.3 | 104 | 0.41 | 57.9 | 4 | 3.13 | 18 | 97 |
| 1:32 | 104 | 200.4 | 35 | 104 | 0.32 | 91.8 | 3 | 2.58 | 6.5 | 96.5 |
| 2:08 | 104 | 208.5 | 34.4 | 104 | 0.32 | 98.6 | 3 | 2.56 | 6.5 | 97 |
| 2:40 | 104 | 213.4 | 33.9 | 104 | 0.32 | 100.6 | 3 | 2.54 | 5.5 | 98 |
| 3:22 | 104 | 219 | 33.7 | 104 | 0.31 | 101 | 3 | 2.5 | 5.5 | 96.5 |
| 4:20 | 91 | 223.4 | 33.6 | 91 | 0.27 | 97 | 2 | 1.94 | 5.5 | 97 |

**Date: May, 1 2007**
**Stage 1**
**Membrane Feed: 50% $H_2$/CO**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | |
| 1:26 | Initial Calibration of TCD: Pure H2 read 94%: Adjust Span | | | | | | | | | |
| | | | | | | | | | | |
| 2:14 | 104 | 127.4 | 35.8 | 104 | 5.73 | 36.5 | 4 | 3.83 | 33 | 95 |
| 2:27 | 104 | 129.4 | 35.6 | 104 | 3.34 | 42.1 | 3 | 3.55 | 24 | 93 |
| 2:49 | 104 | 155.3 | 37.2 | 104 | 3.22 | 47.6 | 3 | 3.46 | 23.5 | 93 |
| 3:14 | 103 | 170.2 | 39.4 | 104 | 3.12 | 50.7 | 6 | 3.32 | 25 | 92 |
| 3:30 | 104 | 176 | 40.6 | 104 | 3.11 | 51.8 | 5 | 3.33 | 24.5 | 92 |
| 3:53 | 103 | 185 | 42.4 | 104 | 3.04 | 52.9 | 7 | 3.23 | 24 | 91.5 |
| 4:15 | 107 | 195.2 | 43.8 | 107 | 3.62 | 53.1 | 3 | 3.57 | 22 | 91.5 |

* Cal gas check 53% (post cal reading was 52%)
* Stage 2 Buffer Tank read 121psig 90% H2
* After Stage 1 flow was stopped, TE702 dropped to 189.4 @ 4:26.
* This is a clear indication that this temp is due to gas flow and not convection through the metal.

**Date: May, 3 2007**
**Stage 1 (Flow initiated at 1:28 pm)**
**Membrane Feed: 50% $H_2$/CO**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | |
| 1:28 | 109 | 318 | 134.5 | 109 | 4.95 | 35.9 | 7 | 4.1 | | |
| | Calibrated analyzer | | | | | | | | | |
| 1:37 | 109 | 309.2 | 112.9 | 109 | 8.01 | 46.4 | 4 | 4.64 | 31.5 | 92 |
| 2:47 | 109 | 331.7 | 112 | 109 | 15.22 | 79.2 | 5 | 4.99 | 40 | 92 |
| 3:37 | 110 | 340.5 | 112.5 | 110 | 13.55 | 82 | 7 | 4.74 | 36.5 | 91.5 |
| 3:47 | 112 | 334.5 | 102.5 | 112 | 4.65 | 81.1 | 6 | 3.91 | 20 | 88 |
| 4:11 | 111 | 327.8 | 87.8 | 111 | 4.54 | 76.7 | 3 | 4.07 | 18.5 | 87 |

* Test Background: Need to get gas through membranes hotter. Gas reject is about 20 degrees C less than inlet temp. Try to purge N2 through pipe

**Date: May, 3 2007**
**Stage 2 (Flow initiated at 3:51)**
**Membrane Feed: 50% $H_2$/CO**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 | | |
| 1:43 | Permeate closed, remained closed until a good H2 | | | | | | | | | |
| 3:40 | Reject reading 87% open permeate | | | | | | | | | |
| 3:51 | 103 | 254.1 | 104.9 | 103 | 0.66 | 91.2 | 4 | 3.77 | 32 | 99 |
| 4:14 | 100 | 256 | 87.2 | 99 | 0.63 | 121.7 | 5 | 3.82 | 34 | 99 |

**Date: May, 9 2007**
**Stage 1**
**Membrane Feed: 50% $H_2$/CO**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | |
| | | | | | | | | | | |
| 11:10 | 99 | 218.4 | 61.8 | 98 | 7.78 | 27.8 | 119 | 0.02 | 49 | |
| 11:12 | | | | | | | | | | |
| 11:16 | 99 | 224.1 | 62.6 | 99 | 6.38 | 33.2 | 6 | 3.9 | 32 | 89 |
| 11:30 | 99 | 227.1 | 58.7 | 99 | 4.41 | 43.2 | 6 | 3.65 | 25 | 88.5 |
| 11:40 | 99 | 227.7 | 57.7 | 99 | 3.99 | 48.9 | 3 | 3.81 | 22.5 | 89 |
| 11:52 | 99 | 229.7 | 56.8 | 99 | 3.94 | 53.8 | 8 | 3.54 | 24 | 88 |
| 12:18 | 99 | 230.6 | 57.4 | 99 | 3.95 | 60.6 | 6 | 3.66 | 23.5 | 90.5 |
| 1:08 | 98 | 232.4 | 60.6 | 98 | 4.05 | 65.8 | 7 | 3.49 | 24 | 90 |
| 1:17 | Stage 2 start | | | | | | | | | |
| 1:43 | 98 | 237 | 67.8 | 98 | 5.05 | 68.3 | 4 | 3.74 | 26 | 93 |
| 2:00 | 98 | 236.5 | 68.2 | 98 | 5.06 | 69.4 | 4 | 3.73 | 26.5 | 93 |
| 2:06 | Recalibrate H2 analyzer | | | | | | | | 51 | 99 |
| 2:21 | 98 | 238.1 | 70.7 | 99 | 5.12 | 69.8 | 7 | 3.57 | 23.5 | 90 |
| 2:44 | 99 | 239.2 | 72.7 | 99 | 5.12 | 71 | 5 | 3.74 | 28 | 91 |
| 2:45 | #1 Heater Fail | | | | | | | | | |
| 3:10 | 99 | 235 | 74.2 | 99 | 5.12 | 72 | 4 | 3.83 | 26 | 90.5 |
| 3:34 | 99 | 237.3 | 75.5 | 100 | 5.38 | 72 | 7 | 3.63 | 28 | 90 |
| 3:48 | 154 | 241.7 | 79.3 | 155 | 7.36 | 77.1 | 8 | 6.28 | 23 | 90.5 |
| 4:06 | 154 | 244.6 | 82.1 | 155 | 7.22 | 88.6 | 4 | 6.51 | 23 | 90 |
| 4:19 | 154 | 243.6 | 83.5 | 155 | 7.25 | 91.1 | 7 | 6.32 | 22 | 90.5 |

**Date: May, 9 2007**

**Stage 2**
**Membrane Feed: 50% $H_2$/CO**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 | | |
| 11:25 | | | | | | | | | 82 | |
| 1:17 | | | | | | | | | 85 | |
| 1:20 | 104 | 209.5 | 39.4 | 104 | 0.47 | 72.4 | 3 | 3.22 | | 98 |
| 1:43 | 104 | 215.8 | 38.8 | 104 | 0.32 | 100.6 | 4 | 2.88 | 5 | 99 |
| 2:00 | 104 | 219.9 | 37.3 | 104 | 0.32 | 104.1 | 3 | 2.54 | 6 | 99 |
| 2:22 | 104 | 224.9 | 37.4 | 103 | 0.31 | 112.6 | 3 | 2.55 | 6 | 97.5 |
| 2:45 | 104 | 229.2 | 37.5 | 103 | 0.32 | 116.2 | 3 | 2.58 | 5 | 99 |
| 3:11 | 104 | 233.2 | 38.1 | 103 | 0.31 | 119 | 3 | 2.6 | 5.5 | 98 |
| 3:35 | 103 | 237.3 | 37.8 | 103 | 0.31 | 120 | 3 | 2.59 | 6 | 97.5 |
| 3:47 | 111 | 239 | 38.6 | 111 | 0.33 | 124 | 4 | 3.14 | 7 | 98 |
| 4:07 | 111 | 240.8 | 38 | 111 | 0.33 | 124.7 | 4 | 2.88 | 6 | 98 |
| 4:20 | 111 | 240.5 | 38.3 | 111 | 0.33 | 125.5 | 4 | 2.9 | 6 | 99 |

**Date: May, 15 2007**
**Stage 1**
**Membrane Feed: PCG**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Reject |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | | |
| 2:05 | Start PCG flow( start feed to PCS) | | | | | | | | | | |
| 2:10 | Flush Stage 1 tank w/PCG- 3 full compression cycles 50-140 psi | | | | | | | | | | |
| 2:45 | Start stage 1 separation | | | | | | | | | | |
| 2:53 | 120 | 238.1 | 53.2 | 121 | 5.43 | 38.7 | 2 | 2.53 | 14.5 | 70 | |
| | Module inlet temperature = 379 degrees F | | | | | | | | | | |
| 3:11 | 118 | 239.9 | 49.4 | 118 | 5.06 | 44.5 | 4 | 2.5 | 13 | 70 | 406.1F |
| 3:28 | 121 | 243.5 | 50.1 | 121 | 5.37 | 47.3 | 7 | 2.5 | 14 | 71 | 405.9F |
| 3:54 | 121 | 247.2 | 51.9 | 121 | 5.5 | 43.9 | 2 | 2.9 | 14 | 76 | 400.4F |
| 4:02 | 118 | 247.6 | 52.8 | 118 | 5.73 | 46.3 | 4 | 2.82 | 14.5 | 77 | 422.0F |
| | Raw H2 concentration in PCG = 33.4% | | | | | | | | | | |

**Date: May, 18 2007**
**Stage 1 (Flow initiated at 2:04 pm)**
**Membrane Feed: PCG**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Reject |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | | |
| 1:20 | Calibrate analyzer: pure H2 read 92%. Analyzer adjusted for zero and 100% span. 50% cal gas test reading 51%. | | | | | | | | | | |
| 1:58 | Stage 1 tank reading 31.5% H2, Start permeate flow. | | | | | | | | | | |
| 2:04 | 116 | 231.3 | 85 | 117 | 7.67 | 37.6 | 4 | 3.05 | 17.5 | 81.5 | |
| 2:32 | 119 | 215.5 | 61.8 | 119 | 8.54 | 38.7 | 1 | 3.44 | 18.5 | 80 | |
| 2:44 | 119 | 223.1 | 66.8 | 119 | 6.22 | 45.5 | 4 | 2.86 | | | |
| 3:00 | 122 | 223 | 65.8 | 122 | 5.82 | 48.2 | 3 | 3.02 | 14.5 | 78.5 | 542.1 |
| 3:15 | 122 | 222.7 | 64.6 | 122 | 5.08 | 49.9 | 2 | 3.09 | 13 | 78 | |
| 3:31 | 117 | 224.8 | 68.4 | 117 | 6.31 | 50.7 | 6 | 2.76 | 16.5 | 79 | |
| 3:51 | 120 | 220.8 | 64.1 | 120 | 6.14 | 46 | 1 | 3.02 | 14 | 78 | |
| 4:01 | 120 | 225 | 69 | 120 | 6.12 | 51.1 | 3 | 2.91 | 14.5 | 77.5 | |
| 4:18 | 121 | 226.2 | 70.8 | 121 | 5.79 | 53.2 | 3 | 2.95 | 14 | 78 | |
| 4:28 | 111 | 227.5 | 73.6 | 111 | 6.05 | 56.2 | 1 | 2.76 | 15.5 | 79 | |
| | Raw PCG H2 reading, 34.5% | | | | | | | | | | |

**Date: May, 18 2007**
**Stage 2 (Flow initiated at 3:42)**
**Membrane Feed: PCG**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 | | |
| | Stage 2 tank reads 60 psi @ 78% H2 | | | | | | | | 30 | 94.5 |
| 3:42 | 55 | 209.8 | 33.6 | 55 | 0.73 | 47.4 | 1 | 1.58 | 41 | 96.5 |
| 3:55 | 56 | 205.1 | 31.3 | 56 | 0.94 | 52.9 | 2 | 1.68 | 47 | 97 |
| 4:05 | 51 | 211 | 38 | 51 | 0.81 | 65 | 2 | 1.47 | 46 | 96.5 |
| | Pure H2 read 98.5, Adjust analyzer span | | | | | | | | | |
| 4:11 | 47 | 214.4 | 40.8 | | 0.74 | Compressor Kicked On | | | | |
| 4:14 | 52 | 214.8 | 40.4 | 52 | 0.84 | 70.4 | 1 | 1.56 | 47 | 98.5 |
| 4:23 | 48 | 216 | 41 | 47 | 0.73 | 73.1 | 2 | 1.35 | 46 | 98 |
| 4:32 | 48 | 218.5 | 43.6 | 48 | 0.76 | 76.4 | 1 | 1.41 | 45.5 | 98 |

**Date: June, 5 2007**
**Stage 2**
**Membrane Feed: PCG**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 | | | |
| 2:30 | Initial PCG H2 concentration was 32% | | | | | | | | | | |
| 3:39 | 124 | 201.4 | 47.9 | 125 | 2.59 | 38.7 | 2 | 1.9 | 74 | 7 | 431 F |
| | Calibrate N2 0% no adjust. H2 reads High: adjust. | | | | | | | | | | |
| | | | | | | | | | | | |

**Date: June, 6 2007**
**Stage 1**
**Membrane Feed: PCG**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | T(F) |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | | |
| 1:33 | Calibrate Analyzer | | | | | | | | | | |
| 2:00 | Check analyzer: 50% gas reads 51% | | | | | | | | | | |
| 2:03 | PCG Reading: 27.5%-28% | | | | | | | | | | |
| 2:07 | 122 | 202.6 | 72.3 | 123 | 8.09 | 34.1 | 6 | 2.75 | 13 | 73 | 464F |
| | Check stage 2 H2 concentration 73%. Keep Mat 1 in tank | | | | | | | | | | |
| 2:17 | 122 | 202.5 | 64.7 | 123 | 6.54 | 36.8 | 2 | 3.07 | 14 | 75 | 476 |
| 2:27 | 122 | 206 | 64 | 123 | 8.27 | 40.3 | 4 | 2.77 | 32 | 74.5 | 444 |
| 2:37 | 123 | 216.5 | 86 | 123 | 8.01 | 44 | 1 | 2.66 | 9 | 72.5 | 451 |
| 2:47 | 123 | 213.6 | 73.8 | 123 | 7.58 | 45 | 3 | 2.54 | 9 | 72 | 461 |
| 2:57 | 123 | 215.6 | 67 | 123 | 7.57 | 46.8 | 6 | 2.48 | 9 | 71.5 | 430 |
| 3:07 | 123 | 218.5 | 62.4 | 123 | 6.61 | 47.8 | 2 | 2.5 | 7 | 71 | 453 |
| 3:17 | 123 | 218.7 | 59.5 | 123 | 7.13 | 48.5 | 4 | 2.49 | 7 | 71 | 451 |
| 3:27 | 123 | 220.2 | 57.7 | 123 | 6.82 | 49.4 | 2 | 2.55 | 6.5 | 71 | 458 |
| 3:37 | 122 | 221.5 | 55.8 | 123 | 7.16 | 49.8 | 4 | 2.52 | 7 | 71 | 461 |
| 3:47 | 122 | 222.1 | 54.4 | 123 | 7.16 | 49.9 | 6 | 2.46 | 7.5 | 71 | 461 |
| 3:57 | 122 | 223.7 | 53.5 | 123 | 6.87 | 50.4 | 3 | 2.49 | 7 | 71 | 463 |
| 4:07 | 130 | 224.6 | 53.3 | 131 | 7.63 | 50.8 | 5 | 2.7 | 7.5 | 71 | 460 |
| 4:17 | 130 | 226.4 | 53.5 | 130 | 9.1 | 51.6 | 2 | 2.94 | 8 | 72.5 | 472 |
| 4:27 | 131 | 226.8 | 52.7 | 131 | 7.5 | 52.2 | 4 | 2.71 | 7.5 | 71 | 459 |
| 4:37 | 129 | 227.9 | 52.9 | 129 | 7.4 | 52.9 | 2 | 2.75 | 6 | 71 | 458 |
| | PCS SHUTDOWN | | | | | | | | | | |
| 4:45 | 124 | 226.8 | 51.8 | 124 | 6.12 | 52.7 | 4 | 2.43 | 6 | 69.5 | 406 |

**Date: June, 7 2007**
**Stage 1 (Flow initiated at 1:47 pm)**
**Membrane Feed: PCG**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | T (f) |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | | |
| 1:37 | 131 | 184.6 | 50.4 | 130 | 9.33 | 39.2 | 4 | 3.01 | 12 | 78.5 | 456 |
| | Recalibrated 100% H2 read 98% | | | | | | | | | | |
| 1:47 | 130 | 188.4 | 48.3 | 131 | 6.48 | 43.3 | 1 | 2.82 | 5.5 | 70.5 | 477 |
| 1:57 | 130 | 191 | 49 | 130 | 7.87 | 45.9 | 4 | 2.86 | 7.5 | 73.5 | 439 |
| 2:07 | 129 | 195.4 | 51.1 | 129 | 7.99 | 48.4 | 6 | 2.81 | 9 | 74 | 453 |
| 2:17 | 130 | 198.4 | 51.6 | 131 | 7.91 | 51 | 4 | 2.86 | 7.5 | 73.5 | 479 |
| 2:27 | 130 | 201.4 | 52.1 | 130 | 7.44 | 52.3 | 6 | 2.74 | 7.5 | 73.5 | 461 |
| 2:37 | 129 | 204.3 | 54.4 | 129 | 8.57 | 53.7 | 4 | 2.92 | 9 | 74.5 | 485 |
| 2:47 | 131 | 207.8 | 54.3 | 131 | 7.75 | 54.7 | 6 | 2.84 | 8.5 | 75 | 477 |
| 2:57 | 130 | 209.4 | 55.2 | 131 | 7.93 | 55.7 | 3 | 2.95 | 7.5 | 75 | 488 |
| 3:07 | 130 | 211.2 | 55.3 | 130 | 7.11 | 56.3 | 6 | 2.78 | 8 | 73 | 482 |
| 3:17 | 130 | 213.3 | 55.3 | 130 | 7.27 | 56.8 | 3 | 2.87 | 7 | 72.5 | 485 |
| 3:27 | 130 | 215.2 | 55.7 | 131 | 7.55 | 57.1 | 5 | 2.88 | 7.5 | 72.5 | 475 |
| 3:34 | Recalibrated H2 @ 100% | | | | | | | | | | |
| 3:37 | 131 | 216.6 | 55.5 | 131 | 7.09 | 57.7 | 3 | 2.88 | 6 | 72.5 | 485 |
| 3:47 | 131 | 219 | 55.6 | 131 | 6.76 | 57.9 | 5 | 2.75 | 6.5 | 71.5 | 482 |
| 3:57 | 130 | 220.7 | 56.9 | 130 | 8.42 | 57.9 | 3 | 3.03 | 7.5 | 73.5 | 491 |
| 4:07 | 130 | 222.6 | 57.1 | 130 | 7.58 | 58.1 | 5 | 2.85 | 7 | 73 | 470 |
| 4:17 | 131 | 222.2 | 57 | 131 | 7.14 | 58.4 | 2 | 2.9 | 6 | 73 | 469 |
| 4:29 | 128 | 217.7 | 56.6 | 128 | 6.72 | 58.4 | 5 | 2.73 | 6.5 | 71.5 | 427 |

**Date: June, 7 2007**
**Stage 2 (Flow initiated at 3:01 pm)**
**Membrane Feed: PCG**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 | | | |
| | Stage 2 H2 concentration read 75% | | | | | | | | | | |
| 3:01 | 100 | 207.6 | 58.8 | 100 | 5.36 | 39.9 | 56 | 2.22 | 75.5 | 98.5 | 417 |
| 3:11 | 99 | 217.7 | 70 | 99 | 5.34 | 71.7 | 11 | 2.79 | 63 | 95 | 412 |
| 3:21 | 95 | 228.4 | 76.1 | 95 | 5.25 | 87.1 | 9 | 2.82 | 59.5 | 96.5 | 433 |
| | Reject flow was too high, adjusted, stage 2 tank was at 89 PSIG | | | | | | | | | | |
| 3:31 | 93 | 223.1 | 65.4 | 93 | 0.46 | 84.5 | 5 | 2.38 | 17 | 94 | 412 |
| 3:41 | 89 | 224.5 | 60.5 | 89 | 0.46 | 84 | 6 | 1.46 | 11 | 92.5 | 411 |
| 3:51 | 84 | 227.8 | 61.9 | 89 | 0.8 | 90.8 | 6 | 2.13 | 21 | 93.5 | 426 |
| 4:01 | 85 | 230.5 | 59.3 | 85 | 0.7 | 91.1 | 7 | 1.63 | 20 | 94 | 439 |
| 4:11 | 80 | 232.2 | 57.5 | 80 | 0.64 | 93.1 | 5 | 1.65 | 21 | 94 | 428 |
| 4:21 | 81 | 231.9 | 56.7 | 81 | 0.65 | 94.6 | 4 | 1.64 | 20 | 94 | 424 |
| 4:31 | 75 | 226.4 | 55.1 | 74 | 0.59 | 93.6 | 4 | 1.44 | 20 | 94.5 | 394 |

**Date: June, 8 2007**
**Stage 1 (Flow initiated at 1:01 pm)**
**Membrane Feed: PCG**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Reject |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | | |
| | | | | | | | | | | | |
| 12:51 | Calibrate Analyzer adjust to 100% H2, zero was good, 50% H2 read 52% | | | | | | | | | | |
| 12:59 | Test stage 1 tank 31% H2 | | | | | | | | | | |
| 1:01 | 131 | 183.9 | 48.6 | 131 | 8.6 | 37 | 4 | 3.07 | 12 | 76.5 | 440 |
| 1:11 | 131 | 184.5 | 44.3 | 131 | 6.68 | 40.6 | 6 | 2.79 | 7 | 72.5 | 391 |
| 1:21 | 130 | 187.2 | 46.9 | 130 | 8.21 | 44.8 | 3 | 3.02 | 8 | 75 | 397 |
| 1:33 | 128 | 192.6 | 48.4 | 128 | 8.3 | 49.1 | 2 | 3.03 | 7.5 | 76.5 | 475 |
| 1:43 | 131 | 196.1 | 51.8 | 131 | 8.39 | 51.7 | 4 | 3 | 8.5 | 76.5 | 474 |
| 1:53 | 130 | 199.2 | 53.2 | 130 | 8.19 | 54.4 | 1 | 3.11 | 7 | 76 | 466 |
| 2:03 | 130 | 201.2 | 54 | 130 | 7.6 | 55.5 | 4 | 2.9 | 7.5 | 75.5 | 437 |
| 2:13 | 130 | 204.6 | 57.4 | 130 | 9.12 | 57.4 | 1 | 3.2 | 9 | 77 | 474 |
| 2:23 | 129 | 206.4 | 58.6 | 130 | 8.88 | 57.9 | 4 | 3.03 | 9.5 | 78 | 465 |
| 2:33 | 125 | 206.9 | 58.8 | 125 | 8.25 | 58.5 | 1 | 2.96 | 8.5 | 76.5 | 470 |
| 2:44 | 131 | 208 | 59.2 | 131 | 8.22 | 58.9 | 4 | 2.94 | 8.5 | 77.5 | 472 |
| 2:54 | 130 | 208.8 | 59.6 | 131 | 8.29 | 59.3 | 1 | 3.12 | 7.5 | 76.5 | 472 |
| 3:04 | 130 | 209.3 | 59.5 | 131 | 7.75 | 59.5 | 4 | 2.88 | 7 | 76.5 | 466 |
| | 130 | 210.6 | 60 | 130 | 8.78 | 59.7 | 2 | 3.13 | 7.5 | 76.5 | 446 |
| 3:27 | 130 | 211.3 | 61.2 | 130 | 8.4 | 59.7 | 4 | 2.94 | 9 | 77.5 | 462 |
| | 131 | 212.9 | 61.8 | 131 | 7.83 | 60.3 | 2 | 3.01 | 7.5 | 77.5 | 419 |
| 3:52 | 130 | 213.2 | 62.2 | 130 | 8.12 | 60.6 | 5 | 2.89 | 8.5 | 778 | 398 |
| 4:03 | 131 | 213.9 | 63.2 | 131 | 8.01 | 61.1 | 3 | 2.97 | 8 | 78.5 | 405 |
| 4:15 | 130 | 214.4 | 63.1 | 130 | 8.41 | 61.2 | 1 | 3.15 | 7 | 70.5 | 473 |
| 4:44 | 118 | 212.7 | 63 | 118 | 6.94 | 60.9 | 3 | 2.54 | 7 | 70.5 | 384 |

**Date: June, 8 2007**

**Stage 2 (Flow initiated at 2:36)**
**Membrane Feed: PCG**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 | | | |
| 2:32 | Stage 2 tank H2 concentration 74% @ 111 psi | | | | | | | | | | |
| 2:36 | 101 | 182.8 | 39.2 | 101 | 0.41 | 52.2 | 1 | 1.28 | 9 | 98 | 447 |
| 2:47 | 100 | 183.9 | 52.8 | 99 | 0.44 | 68 | 1 | 1.35 | 21 | 95.5 | 425 |
| 2:56 | 101 | 182.7 | 40.4 | 101 | 0.36 | 66.7 | 1 | 1.05 | 13.5 | 95.5 | 456 |
| 3:06 | 100 | 182.5 | 42.4 | 100 | 0.36 | 72.5 | 1 | 1.15 | | 97 | 416 |
| 3:14 | Stage 2 reject reading malfunction(too high) | | | | | | | | | | |
| 3:21 | 100 | 182.1 | 44.4 | 100 | 0.33 | 78.4 | 0 | 0.95 | | 96 | 418 |
| 3:30 | 96 | 181.8 | 46.1 | 96 | 0.29 | 81.7 | 0 | 0.96 | 5.5 | 97.5 | 403 |
| 3:43 | 99 | 181.7 | 45.6 | 98 | 0.32 | 81.5 | 0 | 0.87 | 5.5 | 95.5 | 404 |
| 3:55 | 95 | 181 | 45.4 | 95 | 0.3 | 81.6 | 0 | 0.83 | 4 | 98 | 465 |
| 4:05 | 96 | 181.7 | 48 | 96 | 0.56 | 88.8 | 1 | 1.62 | 8.5 | >100 | 468 |
| 4:08 | Recalibrated 50% H2, read 55.5% | | | | | | | | | | |
| 4:19 | 96 | 181.4 | 48.3 | 96 | 0.52 | 91.5 | 1 | 1.39 | | 92 | |
| 4:22 | Recalibrated 50% H2, read 52: stage 2 tank dropped below 90 PSIG | | | | | | | | | | |
| 4:25 | 93 | 181 | 49.9 | 93 | 0.48 | 92.3 | 0 | 1.28 | 8 | 89.5 | 460 |
| 4:35 | 89 | 180.4 | 49.1 | 89 | 0.42 | 92.1 | 0 | 1.1 | 7.5 | 90 | 462 |
| 4:46 | 91 | 177.4 | 49 | 90 | 0.4 | 92 | 0 | 1.06 | 5.5 | 89.5 | 446 |

**Date: July, 24 2007**
**Stage 1 (Flow simultaneously with stage 2)**
**Membrane Feed: 50% $H_2$/CO**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Reject |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 | | | |
| | Run 50/50 H2/CO through stages 1 and 2 | | | | | | | | | | |
| 1:55 | Calibrate analyzer, calibrate gas = 49.5 } 2 bottles of same gas, sample gas = 50% | | | | | | | | | | |
| | Initiate flow through permeate side | | | | | | | | | | |
| 2:04 | 102 | 179 | 48.5 | 103 | 1.95 | 32.7 | 1 | 2.02 | 38 | 73.5 | |
| 2:15 | 103 | 182 | 45.5 | 103 | 2.5 | 34.9 | 2 | 2.07 | 4 | 69 | 327 |
| 2:25 | 103 | 182.5 | 43.1 | 103 | 2.01 | 36.3 | 0 | 2.01 | 1 | 64.5 | 345 |
| 2:35 | 103 | 184.9 | 41.1 | 103 | 1.88 | 37.4 | 2 | 2.02 | 3 | 65 | 342 |
| 2:45 | 103 | 186.4 | 39 | 103 | 1.99 | 38.4 | 1 | 2 | 2 | 64.5 | 317 |
| 2:55 | 103 | 188.7 | 37.5 | 103 | 2.37 | 39.3 | 1 | 2.1 | 1 | 64.5 | 321 |
| 3:05 | 103 | 188.8 | 36.4 | 103 | 2.41 | 39.8 | 2 | 2.12 | 2 | 66 | 366 |
| 3:15 | 103 | 191.5 | 35.4 | 103 | 2.33 | 40.4 | 1 | 2.09 | 1 | 66.5 | 353 |
| 3:25 | 103 | 192.4 | 34.5 | 103 | 2.23 | 40.9 | 1 | 2.09 | 1.5 | 67 | 325 |
| 3:36 | 103 | 194 | 33.7 | 103 | 2.24 | 41.4 | 1 | 2.07 | 1 | 66.5 | 343 |
| 3:45 | 103 | 195.2 | 33.4 | 103 | 2.2 | 41.6 | 1 | 2.03 | 2 | 65.5 | 353 |
| 3:55 | 103 | 196.3 | 33.1 | 103 | 2.22 | 41.5 | 1 | 2.04 | 1 | 64 | 344 |
| 4:10 | 103 | 197.6 | 32.5 | 103 | 2.11 | 42.1 | 1 | 2.02 | 1 | 63 | 313 |
| 4:21 | Recalibrate 50/50 H2/CO, Read 49% | | | | | | | | | | |
| 4:23 | 102 | 198.4 | 32.1 | 102 | 2.19 | 42 | 1 | 2.02 | 1 | 62.5 | 360 |
| 4:28 | Adjust Reject Flows | | | | | | | | | | |
| 4:33 | 103 | 199.7 | 32.1 | 103 | 2.65 | 42.1 | 2 | 2.03 | 1.5 | 64.5 | 344 |
| 4:43 | 103 | 200.7 | 32.2 | 103 | 2.35 | 42.3 | 1 | 1.88 | 8 | 64.5 | 351 |
| 4:56 | 101 | 202.7 | 35 | 101 | 2.7 | 42.9 | 2 | 2.1 | 5 | 67.5 | 323 |

**Date: July, 24 2007**

**Stage 2 (Flow simultaneously with stage 1)**
**Membrane Feed: 50% $H_2$/CO**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | | (%H2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Reject | Permeate | Cor.Reject |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 | | | |
| 2:27 | Reject flow initially 50% initiate permeate flow | | | | | | | | | | |
| 2:28 | 103 | 210.6 | 60.3 | 103 | 2.11 | 50.6 | 1 | 1.49 | 26 | 92 | 338 |
| 2:38 | 103 | 209.6 | 55.3 | 103 | 1.13 | 55.3 | 0 | 1.13 | 12 | 90.5 | 350 |
| 2:48 | 103 | 210.4 | 54.1 | 103 | 0.97 | 58.3 | 0 | 1.02 | 14 | 89.5 | 345 |
| 2:58 | 103 | 211.9 | 52.4 | 103 | 0.98 | 61.5 | 0 | 0.94 | 8 | 89 | 353 |
| 3:08 | 103 | 213.1 | 51.3 | 103 | 0.72 | 63.3 | 0 | 0.85 | 6.5 | 88 | 367 |
| 3:18 | 103 | 213.2 | 50.1 | 103 | 0.66 | 65 | 0 | 0.8 | 22 | 87.5 | 352 |
| 3:28 | 103 | 215.2 | 49.8 | 103 | 0.59 | 65.5 | 0 | 0.73 | 5.5 | 87 | 351 |
| 3:38 | 103 | 215.9 | 48.2 | 103 | 0.55 | 66.1 | 0 | 0.68 | 5 | 86 | 353 |
| 3:48 | 103 | 216.2 | 47.8 | 103 | 0.51 | 66.2 | 0 | 0.65 | 4.5 | 86 | 349 |
| 3:58 | 103 | 217.6 | 47.2 | 103 | 0.5 | 66.2 | 0 | 0.64 | 5 | 85 | 354 |
| 4:12 | 103 | 218.7 | 46.1 | 103 | 0.49 | 65.8 | 0 | 0.63 | 3 | 81.5 | 354 |
| 4:21 | Recalibrate 50/50 H2/CO Read 49% and adjusted flows | | | | | | | | | | |
| 4:24 | 102 | 222.8 | 61.6 | 102 | 1.68 | 72.2 | 0 | 1.34 | 19 | 89 | 342 |
| 4:35 | 103 | 224.9 | 64 | 103 | 1.59 | 76 | 0 | 1.31 | 17 | 89 | 354 |
| 4:45 | 102 | 225.7 | 65.6 | 102 | 1.52 | 78.5 | 0 | 1.28 | 17 | 90 | 334 |
| 4:58 | 101 | 227 | 66.1 | 101 | 1.41 | 80.3 | 0 | 1.23 | 16 | 89 | 362 |

**Date: July, 25 2007**
**Stage 1 (Flow simultaneously with stage 2 for 30 minutes)**
**Membrane Feed: 100% $N_2$**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | |
|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 |
| 1:58 | Zero gas reads 0 | | | | | | | |
| 1:58 | 88 | 134.9 | 61.3 | 88 | 26.44 | 36.1 | 0 | 1 |
| 2:07 | 90 | 141.8 | 64.4 | 90 | 23.49 | 35.9 | 0 | 1.02 |
| 2:14 | 90 | 146.8 | 65.9 | 90 | 23.32 | 36 | 0 | 1.02 |
| 2:22 | 90 | 154.1 | 67.8 | 90 | 23.04 | 35.9 | 0 | 1.02 |
| 2:29 | 90 | 160.8 | 69.6 | 90 | 22.85 | 35.8 | 0 | 1.02 |
| | After pure H2 run | | | | | | | |
| 3:41 | 90 | 206.8 | 45.3 | 91 | 9.11 | 87.1 | 0 | 0.99 |
| 3:49 | 90 | 205.8 | 44.6 | 90 | 9.03 | 79.5 | 0 | 0.99 |
| 4:02 | 90 | 201 | 44.4 | 90 | 8.85 | 70.8 | 0 | 0.99 |
| 4:18 | 90 | 193.2 | 44.2 | 90 | 8.37 | 61.7 | 0 | 0.98 |

* Stage 1 permeate showed no detectable flow through the H2 analyzer
* Stage 1 reject showed 0-1% H2 concentration. This was checked at every data point taken
* 50/50 H2/CO blend read 49.5%

**Date: July, 25 2007**
**Stage 2 (Flow simultaneously with stage 1 for 30 minutes)**
**Membrane Feed: 100% $N_2$**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | |
|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 |
| 1:59 | 88 | 196.4 | 68.4 | 88 | 4.06 | 41.8 | 0 | 0.1 |
| 2:08 | 90 | 200.3 | 76.8 | 90 | 4.2 | 42 | 0 | 0.12 |
| 2:15 | 90 | 201.6 | 79.6 | 90 | 4.22 | 42 | 0 | 0.12 |
| 2:23 | 90 | 203.2 | 83.1 | 90 | 4.23 | 42.1 | 0 | 0.12 |
| 2:31 | 90 | 205 | 86.1 | 90 | 4.22 | 42.1 | 0 | 0.12 |
| 3:42 | 91 | 223.1 | 93.6 | 91 | 4.32 | 101.5 | 0 | 0.11 |
| 3:50 | 90 | 223.7 | 96.6 | 90 | 4.29 | 94.5 | 0 | 0.11 |
| 4:03 | 90 | 224.7 | 98.8 | 90 | 4.26 | 85.8 | 0 | 0.12 |
| 4:19 | 90 | 225.3 | 101.1 | 90 | 4.27 | 76.4 | 0 | 0.12 |

* Stage 2 permeate showed no detectable flow through H2 analyze
* Stage 2 reject showed 0-1% H2 concentration at every data point

**Date: July, 25 2007**
**Stage 1 (Initiated flow immediately after 100% $N_2$ simultaneously with stage 2)**
**Membrane Feed: 100% $H_2$**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | |
|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) |
| | PT702 | TE702 | TE709 | PT703 | FIT701 | TE703 | PT704 | FIT702 |
| 2:47 | 104 | 172.9 | 58.8 | 104 | 8.67 | 73.4 | 0 | 10.14 |
| 2:50 | Calibrated 50/50 H2/CO mix: Read 49.5 | | | | | | | |
| 2:54 | 105 | 176.8 | 56.3 | 105 | 1.91 | 90.8 | 1 | 10.1 |
| 3:01 | 105 | 183.1 | 54 | 105 | 2.13 | 99.5 | 1 | 10.24 |
| 3:07 | 105 | 188.6 | 52.2 | 105 | 1.91 | 105.2 | 1 | 10.24 |
| 3:14 | 105 | 193.7 | 50.1 | 105 | 1.88 | 108.8 | 0 | 10.24 |
| 3:21 | 105 | 198.2 | 48.5 | 105 | 1.94 | 111.1 | 1 | 10.24 |

* FIT 702 was maxed out at 10.24 l/min

**Date: July, 25 2007**
**Stage 2 (Initiated flow immediately after 100% $N_2$ simultaneously with stage 1)**
**Membrane Feed: 100% $H_2$**

| | GAS INLET | | GAS REJECT | | | GAS PERMEATE | | |
|---|---|---|---|---|---|---|---|---|
| Time | Press. (PSIG) | Temp. (°C) | Temp. (°C) | Press. (PSIG) | Flow (LPM) | Temp. (°C) | Press. (PSIG) | Flow (LPM) |
| | PT707 | TE705 | TE706 | PT709 | FIT703 | TE710 | PT708 | FIT704 |
| 2:48 | 104 | 206.5 | 80.8 | 104 | 4.03 | 95.1 | 0 | 4.61 |
| 2:55 | 105 | 205.8 | 76.4 | 105 | 1.81 | 109.6 | 0 | 4.73 |
| 3:02 | 105 | 208.9 | 74.7 | 105 | 1.83 | 118.2 | 0 | 4.76 |
| 3:08 | 105 | 211.6 | 73.9 | 105 | 1.84 | 124.7 | 0 | 4.77 |
| 3:15 | 105 | 214.1 | 73.2 | 105 | 1.85 | 129.3 | 0 | 4.78 |
| 3:21 | 105 | 216.5 | 72.9 | 105 | 1.85 | 132.8 | 0 | 4.8 |

# Appendix B: Results summary calculations

**Date: April, 12 2007**
**Stage 1**
**Membrane Feed: 50% He/$N_2$**
**Source Data: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 44.5 | °C |
| Feed Pressure | 95.3 | psig |
| Permeate Pressure | 6.8 | psig |
| Permeate Side Gas Composition | 95% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 16.84 | slpm |
| Permeate Gas Flow | 6.68 | slpm |
| | | |
| Test Gas He input: | 50% | % |
| Test Gas Temperature (Reject): | 44.5 | °C |
| Feed pressure: | 95.3 | psig |
| Feed Partial Pressure He: | 47.7 | psi |
| Permeate Pressure: | 6.8 | psig |
| Permeate side gas composition (%): | 95% | % |
| Permeate Partial Pressure He: | 6.5 | psi |
| He Partial Pressure Diff: | 41.2 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 16.84 | lpm |
| Total He to membrane: | 8.42 | lpm |
| Permeate gas flow: | 6.68 | lpm |
| Recovery rate: | 76% | % |
| Permeance: | 0.432 | $m^3/m^2/hr/bar$ |
| Flux: | 1.95 | scfh/sf/20 psi |

**Date: April, 13 2007**
**Stage 2**
**Membrane Feed: 50% He/$N_2$**
**Source Data: Data Logger**

| | 40 PSIG | 80 PSIG | Units |
|---|---|---|---|
| Reject Temperature | 64.1 | 50.1 | °C |
| Feed Pressure | 42.3 | 80.1 | Psig |
| Permeate Pressure | 5.9 | 13.0 | Psig |
| Permeate Side Gas Composition | 82% | 83% | % |
| Membrane Surface Area | 0.148 | 0.148 | $m^2$ |
| Total Gas Flow to Membrane | 5.2 | 11.7 | slpm |
| Permeate Gas Flow | 2.4 | 5.8 | slpm |
| | | | |
| Test Gas He input: | 50% | 50% | % |
| Test Gas Temperature (Reject): | 64.1 | 50.1 | °C |
| Feed pressure: | 42.3 | 80.1 | psig |
| Feed Partial Pressure He: | 21.1 | 40.0 | psi |
| Permeate Pressure: | 5.9 | 13.0 | psig |
| Permeate side gas composition (%): | 82% | 83% | % |
| Permeate Partial Pressure He: | 4.9 | 10.8 | psi |
| He Partial Pressure Diff: | 16.3 | 29.2 | psi |
| Membrane surface area: | 0.148 | 0.148 | m2 |
| Total gas flow to membrane (lpm): | 5.23 | 11.71 | lpm |
| Total He to membrane: | 2.62 | 5.86 | lpm |
| Permeate gas flow: | 2.38 | 5.76 | lpm |
| Recovery rate: | 75% | 82% | % |
| Permeance: | 0.705 | 0.964 | $m^3/m^2/hr/bar$ |
| Flux: | 3.19 | 4.37 | scfh/sf/20 psi |

**Date: April, 17 2007**
**Stage 1 (Operated from 1:27 pm - 2:20 pm)**
**Stage 2 (Operated from 3:10 pm - 2:20 pm)**
**Membrane Feed: 50% He/$N_2$**
**Source Data: Data Logger**

| | **Stage 1** | **Stage 2** | **Units** |
|---|---|---|---|
| Reject Temperature | 52.5 | 86.4 | °C |
| Feed Pressure | 95.2 | 96.2 | psig |
| Permeate Pressure | 5.5 | 4.8 | psig |
| Permeate Side Gas Composition | 81% | 90% | % |
| Membrane Surface Area | 0.312 | 0.148 | $m^2$ |
| Total Gas Flow to Membrane | 13.3 | 3.1 | slpm |
| Permeate Gas Flow | 6.6 | 2.0 | slpm |
| | | | |
| Test Gas He input: | 50% | 81% | % |
| Test Gas Temperature (Reject): | 52.5 | 86.4 | °C |
| Feed pressure: | 95.2 | 96.2 | psig |
| Feed Partial Pressure He: | 47.6 | 77.7 | psi |
| Permeate Pressure: | 5.5 | 4.8 | psig |
| Permeate side gas composition (%): | 81% | 90% | % |
| Permeate Partial Pressure He: | 4.4 | 4.3 | psi |
| He Partial Pressure Diff: | 43.2 | 73.4 | psi |
| Membrane surface area: | 0.312 | 0.148 | m2 |
| Total gas flow to membrane (lpm): | 13.29 | 3.06 | lpm |
| Total He to membrane: | 6.64 | 2.47 | lpm |
| Permeate gas flow: | 6.61 | 2.04 | lpm |
| Recovery rate: | 80% | 74% | % |
| Permeance: | 0.345 | 0.147 | $m^3/m^2/hr/bar$ |
| Flux: | 1.56 | 0.67 | scfh/sf/20 psi |

**Date: April, 18 2007**
**Stage 1**
**Membrane Feed: 50% $H_2$/CO**
**Source Data: Data Logger**

| | **Stage 1** | **Units** |
|---|---|---|
| Reject Temperature | 58.3 | °C |
| Feed Pressure | 101.7 | psig |
| Permeate Pressure | 5.0 | psig |
| Permeate Side Gas Composition | 89% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 8.6 | slpm |
| Permeate Gas Flow | 4.1 | slpm |
| | | |
| Test Gas $H_2$ input: | 50% | % |
| Test Gas Temperature (Reject): | 58 | °C |
| Feed pressure: | 102 | psig |
| Feed Partial Pressure $H_2$: | 51 | psi |
| Permeate Pressure: | 5 | psig |
| Permeate side gas composition (%): | 89% | % |
| Permeate Partial Pressure $H_2$: | 5 | psi |
| $H_2$ Partial Pressure Diff: | 46 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 8.55 | lpm |
| Total $H_2$ to membrane: | 4 | lpm |
| Permeate gas flow: | 4.06 | lpm |
| Recovery rate: | 85% | % |
| Permeance: | 0.22 | $m^3/m^2/hr/bar$ |
| Flux: | 0.99 | scfh/sf/20 psi |

**Date: April, 18 2007**
**Stage 1**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Sheet**

| | **Stage 1** | **Units** |
|---|---|---|
| Reject Temperature | 56.9 | °C |
| Feed Pressure | 105.5 | psig |
| Permeate Pressure | 6.2 | psig |
| Permeate Side Gas Composition | 89% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 8.9 | slpm |
| Permeate Gas Flow | 4.6 | slpm |
| | | |
| Test Gas He input: | 50% | % |
| Test Gas Temperature (Reject): | 56.9 | °C |
| Feed pressure: | 105.5 | psig |
| Feed Partial Pressure $H_2$: | 52.7 | psi |
| Permeate Pressure: | 6.2 | psig |
| Permeate side gas composition (%): | 89% | % |
| Permeate Partial Pressure $H_2$: | 5.6 | psi |
| $H_2$ Partial Pressure Diff: | 47.2 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 8.91 | lpm |
| Total $H_2$ to membrane: | 4.46 | lpm |
| Permeate gas flow: | 4.59 | lpm |
| Recovery rate: | 92% | % |
| Permeance: | 0.242 | $m^3/m^2/hr/bar$ |
| Flux: | 1.10 | scfh/sf/20 psi |

**Date: April, 18 2007**
**Stage 2**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Logger**

| Data logger Analysis 3:30 - 4:30 | | |
|---|---|---|
| Reject Temperature | 41.2 | °C |
| Feed Pressure | 81.3 | psig |
| Permeate Pressure | 3.2 | psig |
| Permeate Side Gas Composition | 98.5% | % |
| Membrane Surface Area | 0.148 | $m^2$ |
| Total Gas Flow to Membrane | 3.4 | slpm |
| Permeate Gas Flow | 2.9 | slpm |
| | | |
| Test Gas $H_2$ input: | 89% | % |
| Test Gas Temperature (Reject): | 41 | °C |
| Feed pressure: | 81 | psig |
| Feed Partial Pressure $H_2$: | 73 | psi |
| Permeate Pressure: | 3 | psig |
| Permeate side gas composition (%): | 99% | % |
| Permeate Partial Pressure $H_2$: | 3 | psi |
| $H_2$ Partial Pressure Diff: | 69 | psi |
| Membrane surface area: | 0.148 | m2 |
| Total gas flow to membrane (lpm): | 3.38 | lpm |
| Total $H_2$ to membrane: | 3 | lpm |
| Permeate gas flow: | 2.86 | lpm |
| Recovery rate: | 93% | % |
| Permeance: | 0.24 | $m^3/m^2$/hr/bar |
| Flux: | 1.08 | scfh/sf/20 psi |

**Date: April, 24 2007**
**Stage 1 (Initiated flow simultaneously with stage 2)**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 50.9 | °C |
| Feed Pressure | 111.6 | psig |
| Permeate Pressure | 6 | psig |
| Permeate Side Gas Composition | 89.0% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 7.39 | slpm |
| Permeate Gas Flow | 3.72 | slpm |
| | | |
| Test Gas $H_2$ input: | 50% | % |
| Test Gas Temperature (Reject): | 50.9 | °C |
| Feed pressure: | 111.6 | psig |
| Feed Partial Pressure $H_2$: | 55.8 | psi |
| Permeate Pressure: | 6 | psig |
| Permeate side gas composition (%): | 89% | % |
| Permeate Partial Pressure $H_2$: | 5.3 | psi |
| $H_2$ Partial Pressure Diff: | 50.4 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 7.39 | lpm |
| Total $H_2$ to membrane: | 3.69 | lpm |
| Permeate gas flow: | 3.72 | lpm |
| Recovery rate: | 90% | % |
| Permeance: | 0.183 | $m^3/m^2/hr/bar$ |
| Flux: | 0.83 | scfh/sf/20 psi |

**Date: April, 24 2007**
**Stage 2 (Initiated flow simultaneously with stage 1)**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 35.2 | °C |
| Feed Pressure | 102 | psig |
| Permeate Pressure | 3 | psig |
| Permeate Side Gas Composition | 97.0% | % |
| Membrane Surface Area | 0.148 | $m^2$ |
| Total Gas Flow to Membrane | 2.87 | slpm |
| Permeate Gas Flow | 2.54 | slpm |
| | | |
| Test Gas $H_2$ input: | 89% | % |
| Test Gas Temperature (Reject): | 35.2 | °C |
| Feed pressure: | 102 | psig |
| Feed Partial Pressure $H_2$: | 90.8 | psi |
| Permeate Pressure: | 3 | psig |
| Permeate side gas composition (%): | 97% | % |
| Permeate Partial Pressure $H_2$: | 2.9 | psi |
| $H_2$ Partial Pressure Diff: | 87.9 | psi |
| Membrane surface area: | 0.148 | m2 |
| Total gas flow to membrane (lpm): | 2.87 | lpm |
| Total $H_2$ to membrane: | 2.56 | lpm |
| Permeate gas flow: | 2.54 | lpm |
| Recovery rate: | 97% | % |
| Permeance: | 0.165 | $m^3/m^2/hr/bar$ |
| Flux: | 0.75 | scfh/sf/20 psi |

**Date: May, 1 2007**
**Stage 1**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 39.3 | °C |
| Feed Pressure | 104.1 | psig |
| Permeate Pressure | 4.4 | psig |
| Permeate Side Gas Composition | 92.6% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 7.07 | slpm |
| Permeate Gas Flow | 3.47 | slpm |
| | | |
| Test Gas $H_2$ input: | 50% | % |
| Test Gas Temperature (Reject): | 39.3 | °C |
| Feed pressure: | 104.1 | psig |
| Feed Partial Pressure $H_2$: | 52.1 | psi |
| Permeate Pressure: | 4.4 | psig |
| Permeate side gas composition (%): | 93% | % |
| Permeate Partial Pressure $H_2$: | 4.1 | psi |
| $H_2$ Partial Pressure Diff: | 48.0 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 7.07 | lpm |
| Total $H_2$ to membrane: | 3.53 | lpm |
| Permeate gas flow: | 3.47 | lpm |
| Recovery rate: | 91% | % |
| Permeance: | 0.187 | $m^3/m^2/hr/bar$ |
| Flux: | 0.85 | scfh/sf/20 psi |

**Date: May, 3 2007**
**Stage 1 (Flow initiated at 1:28 pm)**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 110.4 | °C |
| Feed Pressure | 110 | psig |
| Permeate Pressure | 5.3 | psig |
| Permeate Side Gas Composition | 90.1% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 12.90 | slpm |
| Permeate Gas Flow | 4.41 | slpm |
| | | |
| Test Gas $H_2$ input: | 50% | % |
| Test Gas Temperature (Reject): | 110.4 | °C |
| Feed pressure: | 110 | psig |
| Feed Partial Pressure $H_2$: | 55 | psi |
| Permeate Pressure: | 5.3 | psig |
| Permeate side gas composition (%): | 90% | % |
| Permeate Partial Pressure $H_2$: | 4.81 | psi |
| $H_2$ Partial Pressure Diff: | 50.2 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 12.90 | lpm |
| Total $H_2$ to membrane: | 6.45 | lpm |
| Permeate gas flow: | 4.41 | lpm |
| Recovery rate: | 62% | % |
| Permeance: | 0.221 | $m^3/m^2/hr/bar$ |
| Flux: | 1.00 | scfh/sf/20 psi |

**Date: May, 3 2007**
**Stage 2 (Flow initiated at 3:51)**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 96.1 | °C |
| Feed Pressure | 101.5 | psig |
| Permeate Pressure | 4.5 | psig |
| Permeate Side Gas Composition | 99.0% | % |
| Membrane Surface Area | 0.148 | $m^2$ |
| Total Gas Flow to Membrane | 4.44 | slpm |
| Permeate Gas Flow | 3.80 | slpm |
| | | |
| Test Gas $H_2$ input: | 90% | % |
| Test Gas Temperature (Reject): | 96.1 | °C |
| Feed pressure: | 101.5 | psig |
| Feed Partial Pressure $H_2$: | 91.5 | psi |
| Permeate Pressure: | 4.5 | psig |
| Permeate side gas composition (%): | 99% | % |
| Permeate Partial Pressure $H_2$: | 4.46 | psi |
| $H_2$ Partial Pressure Diff: | 87.0 | psi |
| Membrane surface area: | 0.148 | m2 |
| Total gas flow to membrane (lpm): | 4.44 | lpm |
| Total $H_2$ to membrane: | 4.00 | lpm |
| Permeate gas flow: | 3.80 | lpm |
| Recovery rate: | 94% | % |
| Permeance: | 0.254 | $m^3/m^2/hr/bar$ |
| Flux: | 1.15 | scfh/sf/20 psi |

**Date: May, 9 2007**
**Stage 1**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Sheet**
**(System operation warm up, initiated at 11:10 am)**

| | | |
|---|---|---|
| Reject Temperature | 65.2 | °C |
| Feed Pressure | 98.7 | psig |
| Permeate Pressure | 5.6 | psig |
| Permeate Side Gas Composition | 90.9% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 8.5 | slpm |
| Permeate Gas Flow | 3.69 | slpm |
| | | |
| Test Gas $H_2$ input: | 50% | % |
| Test Gas Temperature (Reject): | 65.2 | °C |
| Feed pressure: | 98.7 | psig |
| Feed Partial Pressure $H_2$: | 49.3 | psi |
| Permeate Pressure: | 5.6 | psig |
| Permeate side gas composition (%): | 91% | % |
| Permeate Partial Pressure $H_2$: | 5.1 | psi |
| $H_2$ Partial Pressure Diff: | 44.3 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 8.49 | lpm |
| Total $H_2$ to membrane: | 4.24 | lpm |
| Permeate gas flow: | 3.69 | lpm |
| Recovery rate: | 79% | % |
| Permeance: | 0.211 | $m^3/m^2/hr/bar$ |
| Flux: | 0.96 | scfh/sf/20 psi |

**Date: May, 9 2007**
**Stage 1**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Sheet**
**(System operation under high temperatures after approximately four hours)**

| | | |
|---|---|---|
| Reject Temperature | 81.6 | °C |
| Feed Pressure | 154 | psig |
| Permeate Pressure | 6.3 | psig |
| Permeate Side Gas Composition | 90.3% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 13.65 | slpm |
| Permeate Gas Flow | 6.37 | slpm |
| | | |
| Test Gas $H_2$ input: | 50% | % |
| Test Gas Temperature (Reject): | 81.6 | °C |
| Feed pressure: | 154 | psig |
| Feed Partial Pressure $H_2$: | 77 | psi |
| Permeate Pressure: | 6.3 | psig |
| Permeate side gas composition (%): | 90% | % |
| Permeate Partial Pressure $H_2$: | 5.7 | psi |
| $H_2$ Partial Pressure Diff: | 71.3 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 13.65 | lpm |
| Total $H_2$ to membrane: | 6.82 | lpm |
| Permeate gas flow: | 6.37 | lpm |
| Recovery rate: | 84% | % |
| Permeance: | 0.225 | $m^3/m^2/hr/bar$ |
| Flux: | 1.02 | scfh/sf/20 psi |

**Date: May, 9 2007**
**Stage 2 (Flow initiated at 1:20 pm)**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 38.1 | °C |
| Feed Pressure | 106 | psig |
| Permeate Pressure | 3.4 | psig |
| Permeate Side Gas Composition | 98.2% | % |
| Membrane Surface Area | 0.148 | $m^2$ |
| Total Gas Flow to Membrane | 3.12 | slpm |
| Permeate Gas Flow | 2.79 | slpm |
| | | |
| Test Gas $H_2$ input: | 90% | % |
| Test Gas Temperature (Reject): | 38.1 | °C |
| Feed pressure: | 106 | psig |
| Feed Partial Pressure $H_2$: | 95.8 | psi |
| Permeate Pressure: | 3.4 | psig |
| Permeate side gas composition (%): | 98% | % |
| Permeate Partial Pressure $H_2$: | 3.3 | psi |
| $H_2$ Partial Pressure Diff: | 92.4 | psi |
| Membrane surface area: | 0.148 | m2 |
| Total gas flow to membrane (lpm): | 3.12 | lpm |
| Total $H_2$ to membrane: | 2.82 | lpm |
| Permeate gas flow: | 2.79 | lpm |
| Recovery rate: | 97% | % |
| Permeance: | 0.174 | $m^3/m^2/hr/bar$ |
| Flux: | 0.79 | scfh/sf/20 psi |

**Date: May, 15 2007**
**Stage 1**
**Membrane Feed: PCG**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 51.5 | °C |
| Feed Pressure | 119.6 | psig |
| Permeate Pressure | 3.8 | psig |
| Permeate Side Gas Composition | 72.8% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 8.07 | slpm |
| Permeate Gas Flow | 2.65 | slpm |
| | | |
| Test Gas $H_2$ input: | 33% | % |
| Test Gas Temperature (Reject): | 51.48 | °C |
| Feed pressure: | 119.6 | psig |
| Feed Partial Pressure $H_2$: | 39.9 | psi |
| Permeate Pressure: | 3.8 | psig |
| Permeate side gas composition (%): | 73% | % |
| Permeate Partial Pressure $H_2$: | 2.8 | psi |
| $H_2$ Partial Pressure Diff: | 37.2 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 8.07 | lpm |
| Total $H_2$ to membrane: | 2.69 | lpm |
| Permeate gas flow: | 2.65 | lpm |
| Recovery rate: | 72% | % |
| Permeance: | 0.145 | $m^3/m^2/hr/bar$ |
| Flux: | 0.65 | scfh/sf/20 psi |

**Date: May, 18 2007**
**Stage 1 (Flow initiated at 2:04 pm)**
**Membrane Feed: PCG**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 67 | °C |
| Feed Pressure | 119 | psig |
| Permeate Pressure | 3 | psig |
| Permeate Side Gas Composition | 78.8% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 9.21 | slpm |
| Permeate Gas Flow | 2.98 | slpm |
| | | |
| Test Gas $H_2$ input: | 35% | % |
| Test Gas Temperature (Reject): | 67.211 | °C |
| Feed pressure: | 119 | psig |
| Feed Partial Pressure $H_2$: | 41.055 | psi |
| Permeate Pressure: | 2.6667 | psig |
| Permeate side gas composition (%): | 79% | % |
| Permeate Partial Pressure $H_2$: | 2.1022 | psi |
| $H_2$ Partial Pressure Diff: | 38.953 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 9.2089 | lpm |
| Total $H_2$ to membrane: | 3.1771 | lpm |
| Permeate gas flow: | 2.9789 | lpm |
| Recovery rate: | 74% | % |
| Permeance: | 0.168 | $m^3/m^2/hr/bar$ |
| Flux: | 0.76 | scfh/sf/20 psi |

**Date: May, 18 2007**
**Stage 2 (Flow initiated at 3:42)**
**Membrane Feed: PCG**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 40.8 | °C |
| Feed Pressure | 49.2 | psig |
| Permeate Pressure | 1.5 | psig |
| Permeate Side Gas Composition | 97.6% | % |
| Membrane Surface Area | 0.148 | $m^2$ |
| Total Gas Flow to Membrane | 2.22 | slpm |
| Permeate Gas Flow | 1.45 | slpm |
| | | |
| Test Gas $H_2$ input: | 79% | % |
| Test Gas Temperature (Reject): | 40.8 | °C |
| Feed pressure: | 49.2 | psig |
| Feed Partial Pressure $H_2$: | 38.8 | psi |
| Permeate Pressure: | 1.5 | psig |
| Permeate side gas composition (%): | 98% | % |
| Permeate Partial Pressure $H_2$: | 1.5 | psi |
| $H_2$ Partial Pressure Diff: | 37.3 | psi |
| Membrane surface area: | 0.148 | m2 |
| Total gas flow to membrane (lpm): | 2.22 | lpm |
| Total $H_2$ to membrane: | 1.75 | lpm |
| Permeate gas flow: | 1.45 | lpm |
| Recovery rate: | 81% | % |
| Permeance: | 0.223 | $m^3/m^2/hr/bar$ |
| Flux: | 1.01 | scfh/sf/20 psi |

**Date: June, 6 2007**
**Stage 1**
**Membrane Feed: PCG**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 62.7 | °C |
| Feed Pressure | 123.6 | psig |
| Permeate Pressure | 3.6 | psig |
| Permeate Side Gas Composition | 72.0% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 10.10 | slpm |
| Permeate Gas Flow | 2.64 | slpm |
| | | |
| Test Gas $H_2$ input: | 35% | % |
| Test Gas Temperature (Reject): | 62.7 | °C |
| Feed pressure: | 123.6 | psig |
| Feed Partial Pressure $H_2$: | 42.6 | psi |
| Permeate Pressure: | 3.6 | psig |
| Permeate side gas composition (%): | 72% | % |
| Permeate Partial Pressure $H_2$: | 2.6 | psi |
| $H_2$ Partial Pressure Diff: | 40.1 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 10.10 | lpm |
| Total $H_2$ to membrane: | 3.49 | lpm |
| Permeate gas flow: | 2.64 | lpm |
| Recovery rate: | 54% | % |
| Permeance: | 0.132 | $m^3/m^2/hr/bar$ |
| Flux: | 0.60 | scfh/sf/20 psi |

**Date: June, 7 2007**
**Stage 1 (Flow initiated at 1:47 pm)**
**Membrane Feed: PCG**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 54.2 | °C |
| Feed Pressure | 130.1 | psig |
| Permeate Pressure | 4.5 | psig |
| Permeate Side Gas Composition | 73.2% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 10.52 | slpm |
| Permeate Gas Flow | 2.86 | slpm |
| | | |
| Test Gas $H_2$ input: | 35% | % |
| Test Gas Temperature (Reject): | 54.2 | °C |
| Feed pressure: | 130.1 | psig |
| Feed Partial Pressure $H_2$: | 44.9 | psi |
| Permeate Pressure: | 4.5 | psig |
| Permeate side gas composition (%): | 73% | % |
| Permeate Partial Pressure $H_2$: | 3.3 | psi |
| $H_2$ Partial Pressure Diff: | 41.6 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 10.52 | lpm |
| Total $H_2$ to membrane: | 3.63 | lpm |
| Permeate gas flow: | 2.86 | lpm |
| Recovery rate: | 58% | % |
| Permeance: | 0.140 | $m^3/m^2/hr/bar$ |
| Flux: | 0.64 | scfh/sf/20 psi |

**Date: June, 7 2007**
**Stage 2 (Flow initiated at 3:01 pm)**
**Membrane Feed: PCG**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 61.6 | °C |
| Feed Pressure | 85.3 | psig |
| Permeate Pressure | 5.8 | psig |
| Permeate Side Gas Composition | 94.2% | % |
| Membrane Surface Area | 0.148 | $m^2$ |
| Total Gas Flow to Membrane | 3.09 | slpm |
| Permeate Gas Flow | 1.89 | slpm |
| | | |
| Test Gas $H_2$ input: | 73% | % |
| Test Gas Temperature (Reject): | 61.6 | °C |
| Feed pressure: | 85.3 | psig |
| Feed Partial Pressure $H_2$: | 62.4 | psi |
| Permeate Pressure: | 5.7 | psig |
| Permeate side gas composition (%): | 94% | % |
| Permeate Partial Pressure $H_2$: | 5.42 | psi |
| $H_2$ Partial Pressure Diff: | 57.0 | psi |
| Membrane surface area: | 0.148 | m2 |
| Total gas flow to membrane (lpm): | 3.09 | lpm |
| Total $H_2$ to membrane: | 2.26 | lpm |
| Permeate gas flow: | 1.89 | lpm |
| Recovery rate: | 79% | % |
| Permeance: | 0.184 | $m^3/m^2/hr/bar$ |
| Flux: | 0.83 | scfh/sf/20 psi |

**Date: June, 8 2007**
**Stage 1 (Flow initiated at 1:01 pm)**
**Membrane Feed: PCG**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 54.8 | °C |
| Feed Pressure | 129.7 | psig |
| Permeate Pressure | 3 | psig |
| Permeate Side Gas Composition | 76.3% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 11.25 | slpm |
| Permeate Gas Flow | 3.01 | slpm |
| | | |
| Test Gas $H_2$ input: | 35% | % |
| Test Gas Temperature (Reject): | 54.8 | °C |
| Feed pressure: | 129.7 | psig |
| Feed Partial Pressure $H_2$: | 44.8 | psi |
| Permeate Pressure: | 3 | psig |
| Permeate side gas composition (%): | 76% | % |
| Permeate Partial Pressure $H_2$: | 2.3 | psi |
| $H_2$ Partial Pressure Diff: | 42.5 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 11.25 | lpm |
| Total $H_2$ to membrane: | 3.88 | lpm |
| Permeate gas flow: | 3.01 | lpm |
| Recovery rate: | 59% | % |
| Permeance: | 0.151 | $m^3/m^2/hr/bar$ |
| Flux: | 0.68 | scfh/sf/20 psi |

**Date: June, 8 2007**
**Stage 2 (Flow initiated at 2:36)**
**Membrane Feed: PCG**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 46.2 | °C |
| Feed Pressure | 96 | psig |
| Permeate Pressure | 0.4 | psig |
| Permeate Side Gas Composition | 94.2% | % |
| Membrane Surface Area | 0.148 | $m^2$ |
| Total Gas Flow to Membrane | 1.51 | slpm |
| Permeate Gas Flow | 1.11 | slpm |
| | | |
| Test Gas $H_2$ input: | 76% | % |
| Test Gas Temperature (Reject): | 46.2 | °C |
| Feed pressure: | 96 | psig |
| Feed Partial Pressure $H_2$: | 73.2 | psi |
| Permeate Pressure: | 0.4 | psig |
| Permeate side gas composition (%): | 94% | % |
| Permeate Partial Pressure $H_2$: | 0.3 | psi |
| $H_2$ Partial Pressure Diff: | 72.9 | psi |
| Membrane surface area: | 0.148 | m2 |
| Total gas flow to membrane (lpm): | 1.51 | lpm |
| Total $H_2$ to membrane: | 1.15 | lpm |
| Permeate gas flow: | 1.11 | lpm |
| Recovery rate: | 91% | % |
| Permeance: | 0.085 | $m^3/m^2/hr/bar$ |
| Flux: | 0.38 | scfh/sf/20 psi |

**Date: July, 24 2007**
**Stage 1 (Flow simultaneously with stage 2)**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 37.6 | °C |
| Feed Pressure | 102.9 | psig |
| Permeate Pressure | 1.1 | psig |
| Permeate Side Gas Composition | 65.9% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 4.24 | slpm |
| Permeate Gas Flow | 2.05 | slpm |
| | | |
| Test Gas $H_2$ input: | 50% | % |
| Test Gas Temperature (Reject): | 37.6 | °C |
| Feed pressure: | 103 | psig |
| Feed Partial Pressure $H_2$: | 51.4 | psi |
| Permeate Pressure: | 1.1 | psig |
| Permeate side gas composition (%): | 66% | % |
| Permeate Partial Pressure $H_2$: | 0.8 | psi |
| $H_2$ Partial Pressure Diff: | 50.7 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 4.24 | lpm |
| Total $H_2$ to membrane: | 2.12 | lpm |
| Permeate gas flow: | 2.05 | lpm |
| Recovery rate: | 64% | % |
| Permeance: | 0.074 | $m^3/m^2/hr/bar$ |
| Flux: | 0.34 | scfh/sf/20 psi |

**Date: July, 24 2007**
**Stage 2 (Flow simultaneously with stage 1)**
**Membrane Feed: 50% $H_2$/CO**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 54.2 | °C |
| Feed Pressure | 102.7 | psig |
| Permeate Pressure | 0 | psig |
| Permeate Side Gas Composition | 87.6% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 1.87 | slpm |
| Permeate Gas Flow | 0.93 | slpm |
| | | |
| Test Gas $H_2$ input: | 50% | % |
| Test Gas Temperature (Reject): | 54.2 | °C |
| Feed pressure: | 103 | psig |
| Feed Partial Pressure $H_2$: | 51.35 | psi |
| Permeate Pressure: | 0 | psig |
| Permeate side gas composition (%): | 88% | % |
| Permeate Partial Pressure $H_2$: | 0 | psi |
| $H_2$ Partial Pressure Diff: | 51.35 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 1.87 | lpm |
| Total $H_2$ to membrane: | 0.93 | lpm |
| Permeate gas flow: | 0.93 | lpm |
| Recovery rate: | 87% | % |
| Permeance: | 0.044 | $m^3/m^2/hr/bar$ |
| Flux: | 0.20 | scfh/sf/20 psi |

**Date: July, 25 2007**
**Stage 1 (Flow simultaneously with stage 2 for 30 minutes)**
**Membrane Feed: 100% $N_2$**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 54.5 | °C |
| Feed Pressure | 90.0 | psig |
| Permeate Pressure | 0 | psig |
| Permeate Side Gas Composition | 0.0% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 15.94 | slpm |
| Permeate Gas Flow | 1.00 | slpm |
| | | |
| Test Gas $H_2$ input: | 0% | % |
| Test Gas Temperature (Reject): | 54.5 | °C |
| Feed pressure: | 90 | psig |
| Feed Partial Pressure $H_2$: | 0 | psi |
| Permeate Pressure: | 0 | psig |
| Permeate side gas composition (%): | 100% | % |
| Permeate Partial Pressure Hv: | 0 | psi |
| $H_2$ Partial Pressure Diff: | 0 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 15.94 | lpm |
| Total $H_2$ to membrane: | 0 | lpm |
| Permeate gas flow: | 1.00 | lpm |
| Recovery rate: | N/A | % |
| Permeance: | 0.031 | $m^3/m^2/hr/bar$ |
| Flux: | 0.14 | scfh/sf/20 psi |

**Date: July, 25 2007**
**Stage 2 (Flow simultaneously with stage 1 for 30 minutes)**
**Membrane Feed: 100% $N_2$**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 93.2 | °C |
| Feed Pressure | 90.2 | psig |
| Permeate Pressure | 0 | psig |
| Permeate Side Gas Composition | 0.0% | % |
| Membrane Surface Area | 0.148 | $m^2$ |
| Total Gas Flow to Membrane | 4.38 | slpm |
| Permeate Gas Flow | 0.12 | slpm |
| | | |
| Test Gas $H_2$ input: | 0% | % |
| Test Gas Temperature (Reject): | 93.2 | °C |
| Feed pressure: | 90 | psig |
| Feed Partial Pressure $H_2$: | 0 | psi |
| Permeate Pressure: | 0 | psig |
| Permeate side gas composition (%): | 100% | % |
| Permeate Partial Pressure $H_2$: | 0 | psi |
| $H_2$ Partial Pressure Diff: | 0 | psi |
| Membrane surface area: | 0.148 | m2 |
| Total gas flow to membrane (lpm): | 4.38 | lpm |
| Total $H_2$ to membrane: | 0 | lpm |
| Permeate gas flow: | 0.12 | lpm |
| Recovery rate: | N/A | % |
| Permeance: | 0.008 | $m^3/m^2/hr/bar$ |
| Flux: | 0.03 | scfh/sf/20 psi |

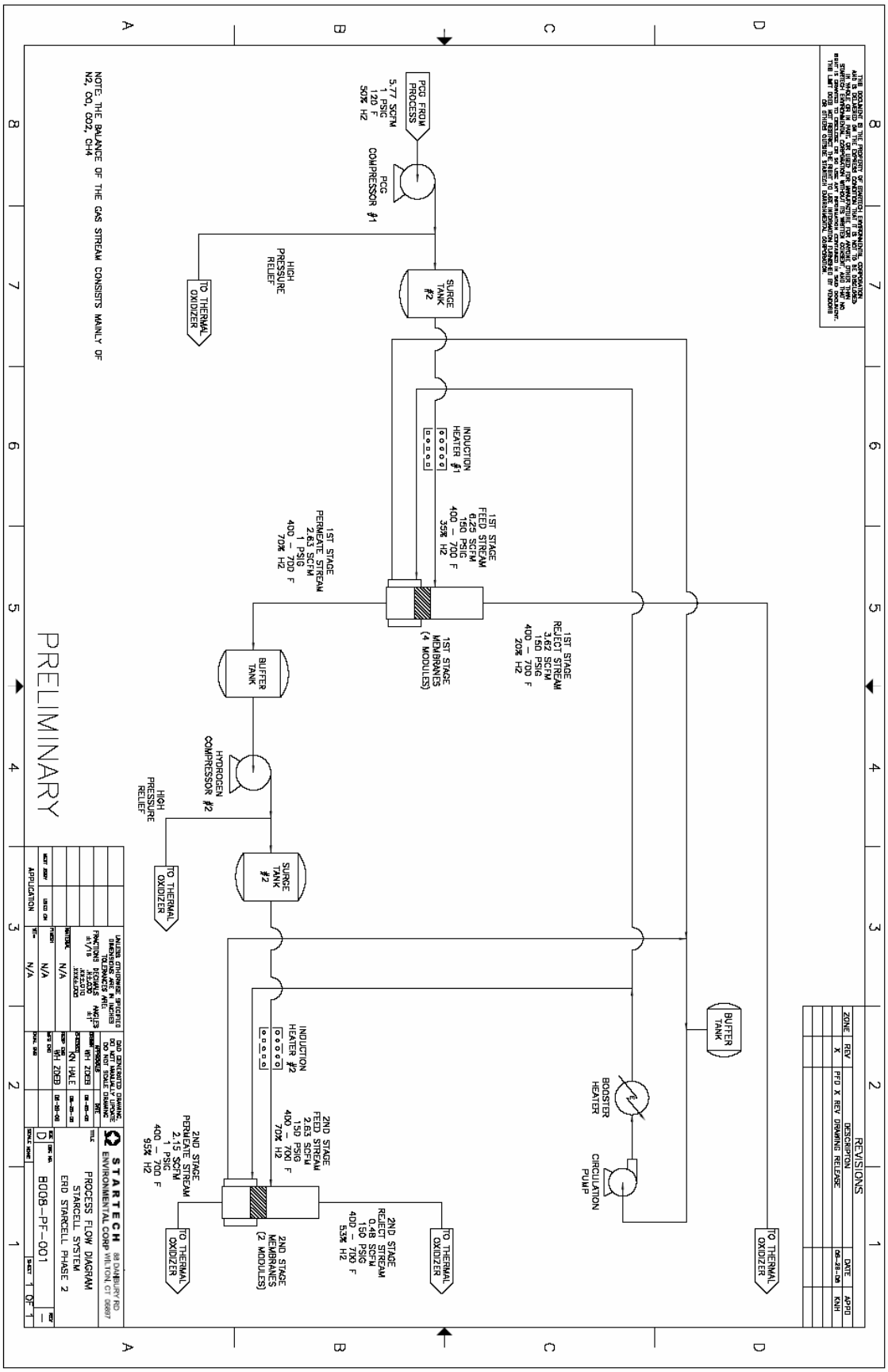
**Date: July, 25 2007**
**Stage 1 (Initiated flow immediately after 100% $N_2$ simultaneously with stage 2)**
**Membrane Feed: 100% $H_2$**
**Data Source: Data Sheet**

| | | |
|---|---|---|
| Reject Temperature | 52.2 | °C |
| Feed Pressure | 105.0 | psig |
| Permeate Pressure | 0.8 | psig |
| Permeate Side Gas Composition | 0.0% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 12.17 | slpm |
| Permeate Gas Flow | 10.21 | slpm |
| | | |
| Test Gas $H_2$ input: | 100% | % |
| Test Gas Temperature (Reject): | 52.2 | °C |
| Feed pressure: | 105 | psig |
| Feed Partial Pressure $H_2$: | 105 | psi |
| Permeate Pressure: | 0.8 | psig |
| Permeate side gas composition (%): | 100% | % |
| Permeate Partial Pressure $H_2$: | 0.8 | psi |
| $H_2$ Partial Pressure Diff: | 104.2 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 12.17 | lpm |
| Total $H_2$ to membrane: | 12.166 | lpm |
| Permeate gas flow: | 10.21 | lpm |
| Recovery rate: | N/A | % |
| Permeance: | 0.271 | $m^3/m^2/hr/bar$ |
| Flux: | 1.23 | scfh/sf/20 psi |

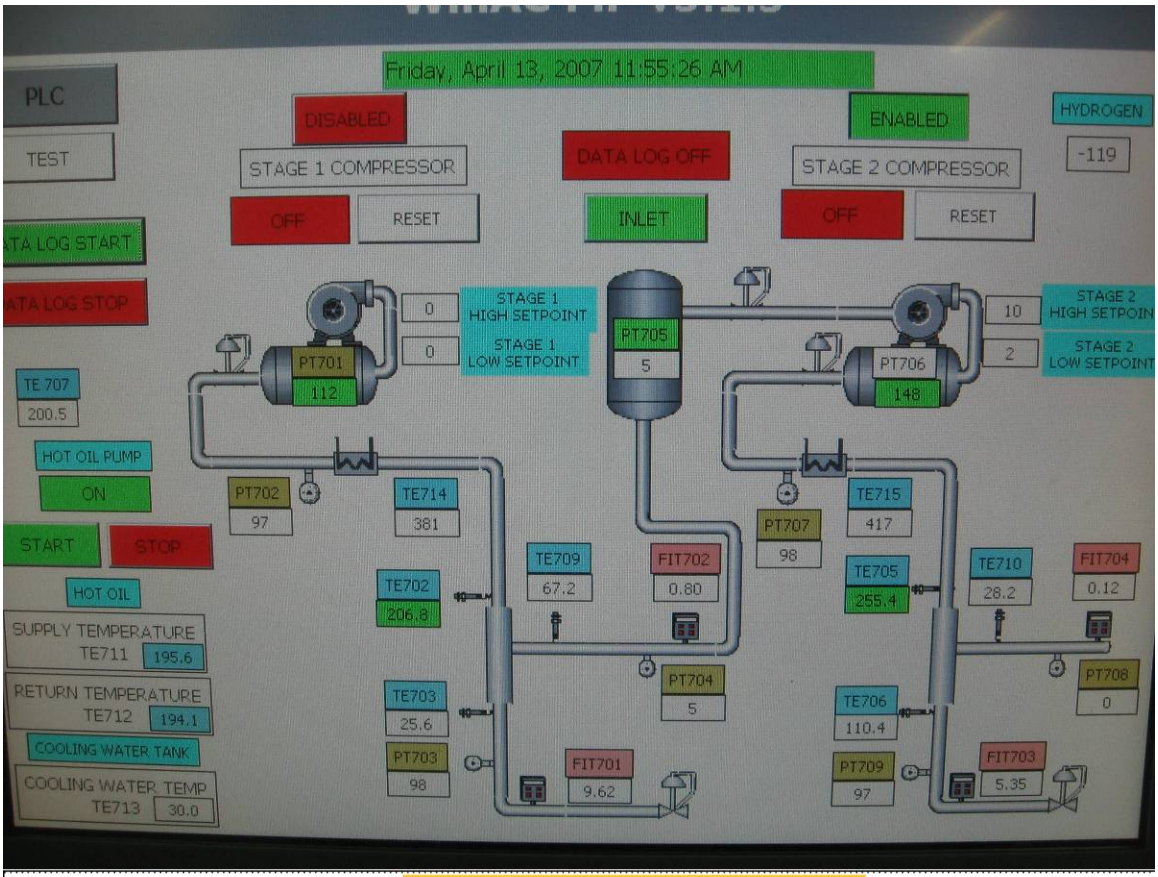
**Date: July, 25 2007**
**Stage 2 (Initiated flow immediately after 100% $N_2$ simultaneously with stage 1)**
**Membrane Feed: 100% $H_2$**
**Data Source: Data Sheet**

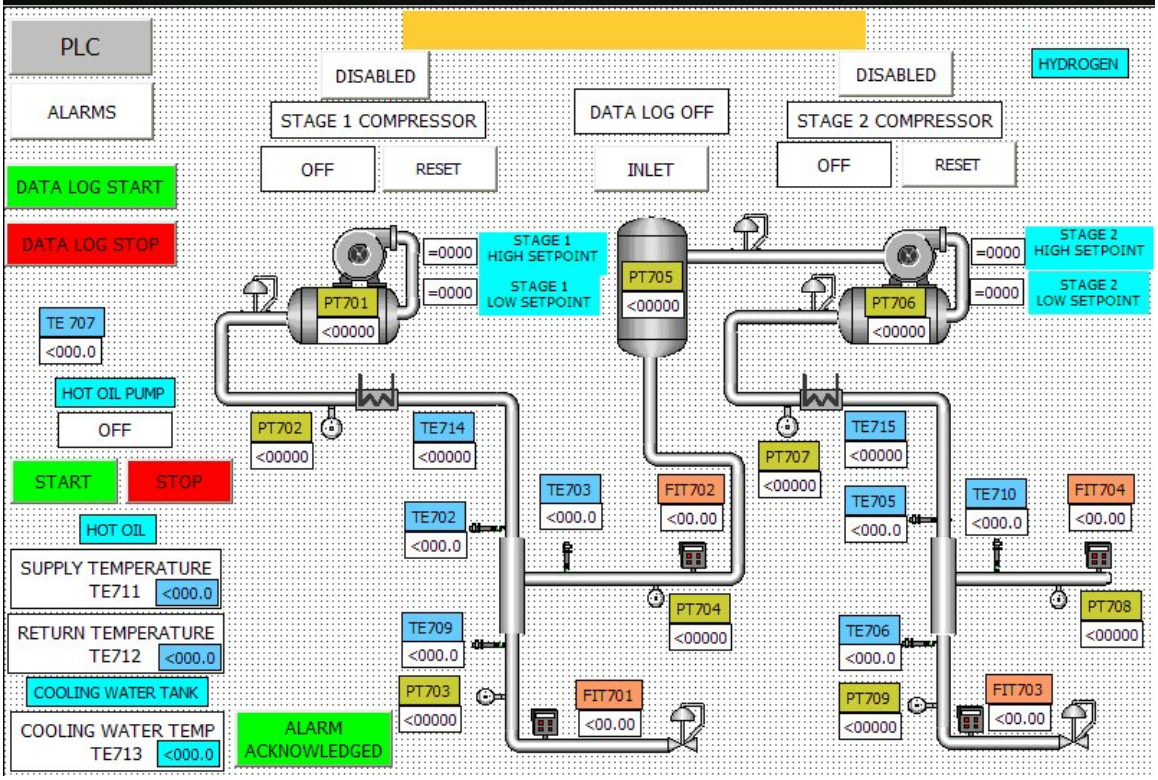
| | | |
|---|---|---|
| Reject Temperature | 73.3 | °C |
| Feed Pressure | 105.0 | psig |
| Permeate Pressure | 0 | psig |
| Permeate Side Gas Composition | 0.0% | % |
| Membrane Surface Area | 0.312 | $m^2$ |
| Total Gas Flow to Membrane | 6.63 | slpm |
| Permeate Gas Flow | 4.78 | slpm |
| | | |
| Test Gas $H_2$ input: | 100% | % |
| Test Gas Temperature (Reject): | 73.3 | °C |
| Feed pressure: | 105 | psig |
| Feed Partial Pressure $H_2$: | 105 | psi |
| Permeate Pressure: | 0 | psig |
| Permeate side gas composition (%): | 100% | % |
| Permeate Partial Pressure $H_2$: | 0 | psi |
| $H_2$ Partial Pressure Diff: | 105 | psi |
| Membrane surface area: | 0.312 | m2 |
| Total gas flow to membrane (lpm): | 6.63 | lpm |
| Total $H_2$ to membrane: | 6.63 | lpm |
| Permeate gas flow: | 4.78 | lpm |
| Recovery rate: | N/A | % |
| Permeance: | 0.127 | $m^3/m^2/hr/bar$ |
| Flux: | 0.57 | scfh/sf/20 psi |

## Appendix C: StarCell Process Flow Diagram


PRELIMINARY
NOTE: THE BALANCE OF THE GAS STREAM CONSISTS MAINLY OF N2, CO, CO2, CH4
PCG FROM PROCESS
5.77 SCFM
1 PSIG
120 F
50% H2
PCG COMPRESSOR #1
SURGE TANK #2
HIGH PRESSURE RELIEF
TO THERMAL OXIDIZER
INDUCTION HEATER #1
1ST STAGE FEED STREAM
6.25 SCFM
150 PSIG
400 – 700 F
35% H2
1ST STAGE PERMEATE STREAM
2.63 SCFM
1 PSIG
400 – 700 F
70% H2
1ST STAGE REJECT STREAM
3.62 SCFM
150 PSIG
400 – 700 F
20% H2
1ST STAGE MEMBRANES (4 MODULES)
BUFFER TANK
HYDROGEN COMPRESSOR #2
HIGH PRESSURE RELIEF
TO THERMAL OXIDIZER
SURGE TANK #2
INDUCTION HEATER #2
2ND STAGE FEED STREAM
2.63 SCFM
150 PSIG
400 – 700 F
70% H2
2ND STAGE PERMEATE STREAM
2.15 SCFM
1 PSIG
400 – 700 F
95% H2
2ND STAGE REJECT STREAM
0.48 SCFM
150 PSIG
400 – 700 F
53% H2
2ND STAGE MEMBRANES (2 MODULES)
TO THERMAL OXIDIZER
BUFFER TANK
BOOSTER HEATER
CIRCULATION PUMP
TO THERMAL OXIDIZER
REVISIONS
ZONE REV DESCRIPTION DATE APPR
X PFD & REV DRAWING RELEASE 08-28-08 KNH
STARTECH ENVIRONMENTAL CORP
PROCESS FLOW DIAGRAM
STARCELL SYSTEM
ERD STARCELL PHASE 2
B008-PF-001
SHEET 1 OF 1

# Appendix D: Process Photos


Friday, April 13, 2007 11:55:26 AM
PLC
TEST
DISABLED
STAGE 1 COMPRESSOR
OFF
RESET
DATA LOG OFF
INLET
ENABLED
STAGE 2 COMPRESSOR
OFF
RESET
HYDROGEN
-119
ATA LOG START
ATA LOG STOP
STAGE 1 HIGH SETPOINT
STAGE 1 LOW SETPOINT
0
0
STAGE 2 HIGH SETPOIN
STAGE 2 LOW SETPOINT
10
2
PT701
112
PT705
5
PT706
148
TE 707
200.5
HOT OIL PUMP
ON
START
STOP
HOT OIL
PT702
97
TE714
381
TE709
67.2
FIT702
0.80
TE702
206.8
PT707
98
TE715
417
TE705
255.4
TE710
28.2
FIT704
0.12
SUPPLY TEMPERATURE
TE711
195.6
RETURN TEMPERATURE
TE712
194.1
COOLING WATER TANK
COOLING WATER TEMP
TE713
30.0
TE703
25.6
PT704
5
TE706
110.4
PT708
0
PT703
98
FIT701
9.62
PT709
97
FIT703
5.35


PLC
ALARMS
DISABLED
STAGE 1 COMPRESSOR
OFF
RESET
DATA LOG OFF
INLET
DISABLED
STAGE 2 COMPRESSOR
OFF
RESET
HYDROGEN
DATA LOG START
DATA LOG STOP
=0000
=0000
STAGE 1 HIGH SETPOINT
STAGE 1 LOW SETPOINT
=0000
=0000
STAGE 2 HIGH SETPOINT
STAGE 2 LOW SETPOINT
PT701
<00000
PT705
<00000
PT706
<00000
TE 707
<000.0
HOT OIL PUMP
OFF
START
STOP
HOT OIL
PT702
<00000
TE714
<00000
TE703
<000.0
FIT702
<00.00
PT707
<00000
TE715
<00000
TE705
<000.0
TE710
<000.0
FIT704
<00.00
TE702
<000.0
SUPPLY TEMPERATURE
TE711
<000.0
PT704
<00000
PT708
<00000
RETURN TEMPERATURE
TE712
<000.0
TE709
<000.0
TE706
<000.0
COOLING WATER TANK
PT703
<00000
FIT701
<00.00
PT709
<00000
FIT703
<00.00
COOLING WATER TEMP
TE713
<000.0
ALARM ACKNOWLEDGED


DANGER!
HIGH VOLTAGE
HIGH
TEMPERATURE


FIRST STAGE PERMEATE
HOT OIL RETURN
HOT OIL SUPPLY
FIRST STAGE REJECT


DANGER!
HIGH VOLTAGE
HIGH
TEMPERATURE


Alicat Scientific
+0.00
FE701
MASS FLOW METER
SERIES GFM
FLOW
Dwyer


FE703
MASS FLOW METER
SERIES GFM
FLOW
Dwyer
0-5 L/min
FE704
MASS FLOW METER
SERIES GFM
FLOW
Dwyer